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TRAJECTORY AND PROPULSION CHARACTERISTICS OF COMET RENDEZVOUS OPPORTUNITIES

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SUMMARY

This report presents a new look at spaceflight mission opportunities to the comets in the time period 1975-2000. Previous studies of comet missions have been restricted mainly to the flyby trajectory mode. Although offering short flight times and low launch velocity requirements, comet flybys suffer from the standpoint of scientific information return because of the very high flyby velocities. Current interest is now centered on the rendezvous (orbit matching) mission which allows the spacecraft many months to monitor the variations in physical activity as the comet approaches and passes through perihelion.

This report expands upon earlier work in this area (Friedlander, Niehoff and Waters, 1969) in terms of the scope of mission opportunities available and the comparison of candidate flight modes for performing these missions. Specifically, the objective is to identify promising rendezvous mission opportunities and flight modes in the time period 1975-2000 from the standpoint of trajectory requirements and launch vehicle/payload capabilities. Two ballistic and two low-thrust flight modes are considered. Ballistic flight modes include: (1) direct transfer utilizing three or more velocity impulses, and (2) gravity-assist transfer via the planet Jupiter which eliminates a midcourse propulsive impulse. The low-thrust propulsion modes include application of: (1) nuclear-electric powerplants, and (2) solar-electric powerplants. All trajectories are optimized to effectively maximize payload (net spacecraft mass delivered) for specific flight time and launch vehicle selections. Emphasis is placed on the programmed Titan-class launch vehicle and flight times consistent with delivering a payload of about 1000 pounds to the comet. An additional

constraint generally applied is that the rendezvous point occur in the region 0-200 days before comet perihelion.

Comet mission opportunities are initially selected on the basis of special scientific interest and Earth-based sighting criteria. The sighting criteria refer to the recovery time of the comet by telescopic observation from Earth prior to the time of rendezvous and sufficient brightness afterwards for obtaining spectroscopic measurements. An early recovery provides an accurate update of the comet's position in orbit, thereby easing the spacecraft guidance problem. Spectroscopic measurements made from Earth are considered for the purpose of correlating spacecraft measurements. Although they are thought to be important, the sighting criteria are not necessarily hard constraints dictating mission success value. It is fortunate though that many mission opportunities do satisfy the sighting criteria. Table S-1 lists those comet applications which satisfy these criteria. Those flight modes for which successful missions were found are noted in the last four columns. Note that the nuclear propulsion portion of the study has been devoted almost completely to a study of the Halley/86 mission.

An attractive series of mission opportunities to Comet Encke, a well known short period comet, for the apparitions 1980, 1984, and 1990 has been found. Figure S-1 shows a performance comparison of the three-impulse ballistic and solar-electric flight modes (1980 apparition). It is noted that the 1980 and 1990 apparitions have comparable trajectory characteristics for either flight mode due to the orbital period of Comet Encke being about 3.3 years. Ballistic payload capability is 820-1000 pounds for the Titan 3D/Centaur or Titan 3F/Centaur launch vehicles. A nuclear-electric spacecraft launched by the same Titan class vehicle offers the

TABLE S-I

SUMMARY* OF COMET RENDEZVOUS OPPORTUNITIES

APPARITION YEAR	COMET	BALLISTIC MODES		LOW THRUST MODES	
		MULTIPLE IMPULSE	GRAVITY ASSIST	SOLAR ELECTRIC	NUCLEAR ELECTRIC
1980	ENCKE	X		X	X(90)**
1982	d'ARREST	X	X	X	
1982	GRIGG-SKJELLERUP	X			
1983	KOPFF	X		X	
1984	ENCKE	X		X	
1985	GIACOBINI-ZINNER	O	O		
1986	HALLEY		O	O	X
1987	BORRELLY	O	O		
1988	TEMPLE-2	X			
1991	FAYE	X			
1993	FORBES	X			
1993	SCHAUMASSE	O			
1994	TUTTLE	O			
1995	PERRINE-MRKOS	X			
1996	KOPFF	X			
1998	GIACOBINI-ZINNER	O			

* X INDICATES A PROMISING MISSION PROFILE EXISTS
O INDICATES NO PROMISING PROFILES WERE FOUND
BLANK INDICATES FLIGHT MODE WAS NOT CONSIDERED IN THIS STUDY

** 1990 OPPORTUNITY (SIMILAR IN GEOMETRY TO 1980 OPPORTUNITY)

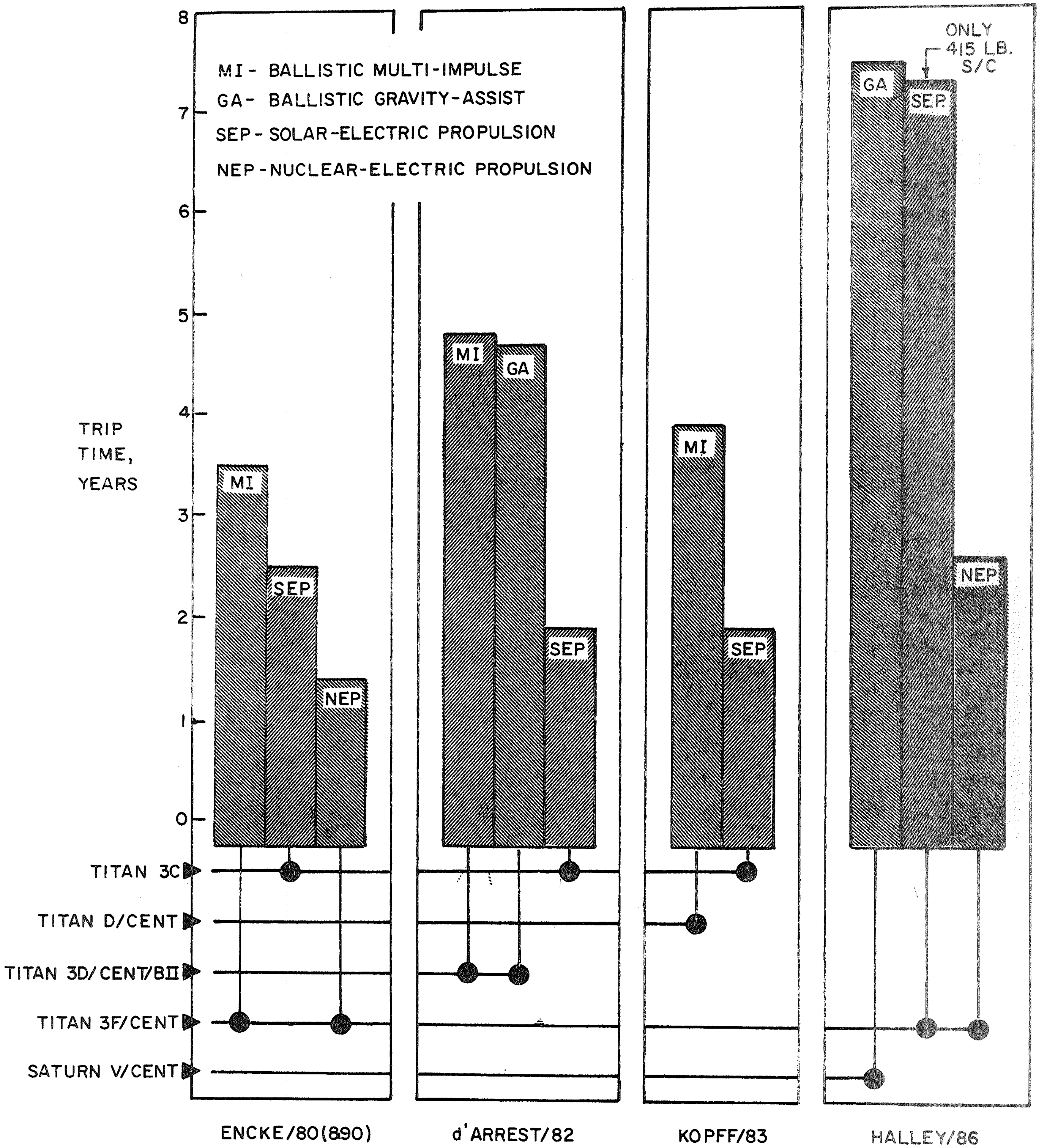

FIGURE S-1. COMET FLIGHT MODE COMPARISONS FOR ∿ 1000 LB. RENDEZVOUS SPACECRAFT advantage of a two year reduction in flight time. A solar-electric spacecraft is also attractive, requiring a Titan 3C launch vehicle and 2.5 years of flight time to deliver 1000 pounds. The Encke/80 mission would provide an early opportunity to develop comet rendezvous technology prior to the arrival of Halley's Comet in 1985.

The d'Arrest/82 mission is characterized by the relatively long flight times required by the ballistic flight modes. The solar-electric mode is much more effective, requiring only a 1.9 year flight time. Shown next are ballistic and solar-electric missions to Kopff/83, the details of which are quite similar to those of the d'Arrest/82 missions. The desirability of missions to these two comets would seem to depend upon the interest of the scientific community in utilizing these opportunities.

The most outstanding comet mission from the standpoint of scientific and public interest is that to Halley's Comet which is due to return in 1985-86. A rendezvous with Halley is especially difficult because of the unique retrograde feature of its orbital motion. Figure S-1 compares the performance characteristics of the ballistic and low-thrust flight modes in achieving a Halley rendezvous. The ballistic mode uses gravity-assist via a Jupiter swingby. In order to deliver a payload of about 1000 pounds ballistically, a Saturn V/Centaur launch vehicle is required and the flight time is almost 8 years. The nuclear-electric spacecraft launched by the less costly Titan 3F/Centaur can deliver a payload in excess of 1000 pounds, and requires a flight time of only 2.6 years. An alternative might be the solar-electric Halley mission, which does not require a nuclear-electric system or a Saturn V launch vehicle but can deliver only 415 pounds with a 7.5-year flight time.

Effective accomplishment of the mission to Halley's Comet would seem to depend upon the development and availability of nuclear-electric propulsion by 1983. At this writing, there is still the possibility that nuclear-electric propulsion would be available in time for the Halley mission or that a commitment of a large ballistic launch vehicle could be made. At least two alternatives yet to be studied are: (1) a solar-electric powered spacecraft employing a large solar collector in order to maintain high power levels throughout the flight, and (2) a combined Jupiter-assist solar-electric mission. If it should turn out that Halley rendezvous is completely impractical, an alternative mission mode might be multiple intercept probes arriving at different points during the comet's perihelion passage.

Certain tentative generalizations concerning comet rendezvous missions are demonstrated in Figure S-1 and were found to apply over the entire group of missions considered. Remembering that Comet Halley is a very unique case, we may conclude that:

1) Ballistic comet rendezvous missions will typically require upwards of four years of flight time and advanced Titan/Centaur launch vehicles.

2) There are no attractive missions for which the Jupiter gravity-assist technique can significantly improve upon the impulsive ballistic flight mode.

3) Solar-electric propulsion can reduce flight times from four years typically required by ballistic flights to about two years.

4) While marginally effective missions to Halley/86 are possible with solar-electric propulsion or Jupiter gravity-assist, the availability of nuclear-electric propulsion would result in a significant improvement in trip time.

Comet rendezvous missions in the time period 1975-2000 are both attractive and feasible from a trajectory/payload standpoint. Several mission profiles utilizing near state-of-the art ballistic flight systems have been identified. The superior performance potential of future nuclear-electric spacecraft has been demonstrated for the Halley mission opportunity. Significant performance improvement can be obtained by using solar-electric propulsion for comet rendezvous missions with the possible exception of Halley/86. An extension of the present study is necessary to complete the picture of comet rendezvous as a class of missions. Subject areas of particular importance to complete mission definition include science objectives, experiment design, transfer guidance, and stationkeeping maneuvers.

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1. INTRODUCTION

Spacecraft missions to the comets have an important role to play in the total space exploration program. Cometary bodies may represent one of the few sources of primordial material accessible in the inner regions of the solar system. Hence, an improved knowledge of comets can contribute to our understanding of the dynamics and origin of the solar system. In particular, "in-situ" scientific measurements can provide information on the comet nucleus and the distribution of particles and fields in the coma and tail regions. This type of data is extremely difficult if not impossible to obtain from Earth-based observations.

Previous reports published by Astro Sciences on the subject of periodic comets have dealt with scientific objectives of comet missions (Roberts, 1964), trajectory and sighting analysis (Narin and Rejzer, 1965), a survey of suitable missions including experimental payload selection and questions of mission constraints (Roberts, 1965), and consideration of the problems of comet orbit determination for unmanned comet probes (Friedlander, 1967). The present report considers the question of comet rendezvous opportunities as opposed to the earlier work which was limited to intercept (flyby) missions. The difference in mission modes is quite significant in terms of science payload and value return, trajectory characteristics, mission operational life time, and launch vehicle requirements. Historically, the flyby mode was given first consideration because it was the conventional approach toward early deep space flight and because it was potentially easy to accomplish in terms of lower launch energy and shorter trip time. It became apparent, however, that the high flyby velocities characteristic of this flight mode were not compatible with many of the science measurement objectives. Clearly, it is most desirable that the spacecraft should match orbits with the comet and thus have many months to monitor the large physical changes which occur as the comet approaches and passes through perihelion.

The rendezvous concept now appears attractive for comet missions in the time period 1975 - 2000 for the following reasons: (1) the expected use of Titan-class launch vehicles allowing the possibility of sufficient injected weight for an on-board propulsion system to accomplish the necessary midcourse and terminal maneuvers, (2) the use of Jupiter gravity-assist for some comet missions thereby reducing the total ΔV requirement, and (3) the advent of low-thrust flight via electric propulsion spacecraft (both solar-electric and nuclear-electric) whose trajectory characteristics are ideally suited for rendezvous with the comets because of the relatively high eccentricity and inclination of cometary orbits. Several studies of comet rendezvous missions have been reported in the literature (Park 1967, Kruse 1968, and Michielsen 1968). The present study will enlarge upon this earlier work in terms of the scope of mission opportunities available and the comparison of candidate modes of flight.

The study objectives are to identify promising comet rendezvous missions from the standpoint of trajectory requirements and launch vehicle/payload capabilities. Particular attention is given to Halley's Comet (1986 apparition) because of the interest and timeliness of this rare opportunity. The following flight modes will be considered:

1) Multiple-impulse ballistic mode
2) Gravity-assisted ballistic mode
3) Nuclear-electric low-thrust mode
4) Solar-electric low-thrust mode.

A particular mission will be considered potentially useful if a 1000 pound payload can be delivered in a total flight time of five years or less. A 1000 pound spacecraft is a useful guideline for assessing comet mission value, being roughly equivalent in exploration capability to the Mariner-Mars 1971 orbiter. The five year flight time limit has been chosen, somewhat arbitrarily, in order to limit spacecraft lifetime requirements and to provide reasonable program lead times for the early mission opportunities.

Mission feasibility depends upon launch vehicle availability as well as performance. In this study we will consider the use of the advanced Titan series of launch vehicles including the Titan 3C and Titan 3D/Centaur configurations which are currently programmed for development. The Titan 3F/Centaur configuration will also be included in the payload analysis so that results of the study will apply in the event that it becomes available. The supplementary Burner II stage will be added to the Titan 3D/Centaur and Titan 3F/Centaur configurations only if a significant payload improvement would result. Saturn-class launch vehicles will not be considered unless they are required to accomplish a particularly difficult but desirable mission such as the Halley/86 opportunity.

This document is the final report on the comet rendezvous opportunities study task and supersedes Technical Memorandum T-21 (Friedlander, Niehoff and Waters, 1969). Section 2 discusses the criteria used in selecting the various mission opportunities to be studied. In Section 3 ballistic and low-thrust flight mode applications and results are presented. Section 4 compares the performance capability of the different flight modes for several promising mission opportunities. It is hoped that this report will be useful to those engaged in the planning of exploratory missions to the periodic comets.

2. COMET SELECTION

Comets are often classified into two groups: 1) a "short-period" group for comets having periods less than 1000 years (usually in the range of 5-10 years), and 2) a "long-period" group for comets with periods greater than 1000 years (typically new parabolic comets). The median orbital elements for the group of short-period comets are:

perihelion, $q = 1.3$ au
semi-major axis, $a = 3.4$ au
eccentricity, $e = 0.56$
inclination, $i = 15°$
period, $P = 7$ years

The short-period comets are "older" in an evolutionary sense than new (long-period) comets and hence are observed to be fainter, less active and generally not very spectacular during their perihelion passes of the sun. However, because of relatively frequent apparitions as seen from the earth their orbits can be determined and future returns predicted with fair accuracy. Hence, the short-period comets are most suitable for rendezvous missions in terms of spaceflight planning requirements. Launch opportunities for such missions occur at an average rate of one per year. When the sighting characteristics of the comet apparitions which are pertinent to rendezvous missions are considered, perhaps only one in four of these opportunities is particularly attractive. The remainder of this section discusses how comet apparitions were evaluated and which were selected as having "good" sighting characteristics to support a rendezvous mission.

2.1 Sighting Criteria

To date virtually all of our knowledge of comets is the result of continued earth-based observations. It should, therefore, not be surprising that earth-based observation plays an important role in the operations of a comet rendezvous mission. Past observations provide an understanding of the stability of the comet's orbit, a key factor in determining acceptable rendezvous trajectories. An early comet recovery by earth-based telescopes can provide a redetermination of the comet's orbit, vital to the final rendezvous maneuvers of the spacecraft. Once rendezvous has been achieved and science measurement operations commence, earth-based observations may provide calibration data and would be useful in correlating spacecraft data with past earth-based comet observations.

These factors can be incorporated into a set of sighting criteria which will serve as guidelines for the systematic selection of potentially good comet apparitions for rendezvous missions. The criteria are as follows:

(1) Earth-based observations be available from two recent apparitions,

(2) Comet recovery and orbit determination be completed at least 20 days before rendezvous,

(3) Observation be possible at total magnitudes less than 12 for a period of 30 days after rendezvous and near the comet's perihelion.

The first criterion adds confidence to predictions of future comet apparitions. This is particularly important to rendezvous missions, which require flight times of several years or more, with the comet usually not observable at the time of launch. It would be most desirable that the comet be recovered and its orbit accurately determined during the two apparitions immediately preceeding the rendezvous passage. For the selection of mission candidates it will be assumed that comet observations will be possible during future apparitions prior to the rendezvous passage.

The second criterion is necessary to insure that minimum comet tracking data be available for guiding the spacecraft to the rendezvous point. Preliminary trajectory surveys reveal that a large class* of rendezvous missions reach the comet approximately 100 days before perihelion. Thus, if the comet can be recovered and observed enough times to redetermine its orbit not later than 120 days before perihelion the spacecraft can still adjust its flight path for rendezvous if the comet's position is within a reasonable predicted uncertainty sphere (10^6 km). Twenty days between final path correction and rendezvous is not conservative but this criterion is "softened" somewhat by the fact that rendezvous spacecraft would almost certainly have an on-board optical tracker to augment earth-based recovery of the comet, thereby enhancing the probability of mission success.

The third criterion makes possible spectroscopic measurements from earth. By correlating such earth-based observations with spacecraft measurements, a maximum amount of scientific information can be obtained from the mission and past observations can be re-examined for proper interpretation. It is possible to obtain spectroscopic data from comets which are fainter than 12th magnitude, but the very largest telescopes (e.g., the 200-inch at Mount Wilson) may be required to do so. To insure that observations are obtained within a period as short as one month the limiting total magnitude was rather arbitrarily set at 12.

* These missions are discussed in considerable detail later in the report.

2.2 Observability

The sighting criteria presented above are requirements on the results of earth-based observation. There are also certain minimum conditions which must be satisfied at the observing site in order to guarantee observability. The following parameters are important:

1) Location of the observatory
2) Darkness of the sky
3) Brightness of the comet
4) Elevation of the comet
5) Daily observation period.

For the purpose of evaluating comet observability the location of the observatory was set at 35° N latitude to be representative of astronomy activity within the United States. A 35° S latitude site was also investigated being typical of Southern Hemisphere observatories. The condition of a dark sky was defined as the center of the sun being at least 18° below the local horizon of the observatory.

There exist two standards for measuring comet brightness (Marsden, 1970), nuclear magnitudes and total magnitudes. Nuclear magnitudes (and an approximation of them referred to as central condensations) are used to predict the stellar brightness of a comet for recovery and tracking purpose. It applies to the brightness of the comet nucleus only but is a good approximation of total brightness when the comet is greater than 1 au from the sun and earth. The generalized expression for nuclear magnitude is given as:

$$m_n = m_{no} + 5 \log 10 \Delta + 5C_n \log 10 r + 0.03\beta \qquad (1)$$

where m_{no} and C_n are constants for each comet, Δ and r are the comet-earth and comet-sun distances respectively, and β is the sun-comet-earth angle measured in degrees. For lesser known comets the last term is often omitted and the expression for brightness referred to as the central condensation.

Total magnitudes are measures of total brightness exhibited by the comet and its expelled matter when the comet is active in the region of its perihelion. Total magnitudes are somewhat less reliable predictions and generally not valid above values of 12. The generalized expression for total magnitude is similar to equation 1 above, being:

$$m_t = m_{to} + 5 \log_{10} \Delta + 5 C_t \log_{10} r \qquad (2)$$

where the variables have similar definitions to those given above. The values of m_{no} and m_{to}, C_n and C_t are different for any particular comet. d'Arrest for example has a value of 15.5 for m_{no} and 9.5 for m_{to}, i.e., a basic brightness difference of 6 magnitudes between the definitions.

Low elevation of the comet above the horizon of the observing site increases the atmospheric path length of an observation and decreases the quality of seeing even in a dark sky. In general, the atmosphere increasingly degrades observability as the comet drops from 25° elevation to the horizon.

The last condition itemized above is the daily period of observation during which the other conditions are satisfied. For recovery and tracking work, plate exposures of up to one hour are needed to detect comets at nuclear magnitudes of 18-21. Although several additional hours may be required to set up an observation run, it is assumed that this can be done before the predicted local rise time of the comet.

2.3 Selection Procedure

The process of selecting comets with favorable earth-based sighting characteristics for rendezvous mission consideration amounts, basically, to determining how well "acceptable" observations satisfy the sighting criteria. By simultaneously generating the trajectories of earth and the comet the conditions of observation described above can be determined as a function of time through the apparition, arbitrarily specified as the period from 300 days before to 300 days after perihelion.

The only difficulty remaining is a proper definition of what constitutes an "acceptable" observation. The location of the observing site and the definition of a dark sky can be taken as hard constraints on observing conditions. However, comet observability deteriorates gradually rather than ceasing abruptly as (1) the brightness decreases (magnitude increases), (2) elevation decreases below 25°, and (3) observation period decreases below one hour. Hence, a set of weighting functions are necessary to evaluate the conditions of brightness, elevation, and observing period. These functions are presented in Figure 1.

From a survey of comet recoveries (Roemer, 1965 and Roemer and Lloyd, 1966) it was found that previously observed short-period comets are usually recovered during the time when their nuclear magnitudes decrease from 21 to 18. Hence, a magnitude weighting factor, W_m, is imposed on observations which gives full value to observing hours when the comet is brighter than $M_n = 18$, no value to the hours when $M_n > 21$ and a linear variation of value from 1 to 0 between these points.

A similar treatment for comet elevation is employed. The elevation weighting factor, W_E, on observing hours is varied from 0 to 1 as the comet rises from the horizon to an elevation of 25°. Above 25° W_E is held at unity, in essence making no allowance for observation quality due to atmospheric distortion at higher elevations.

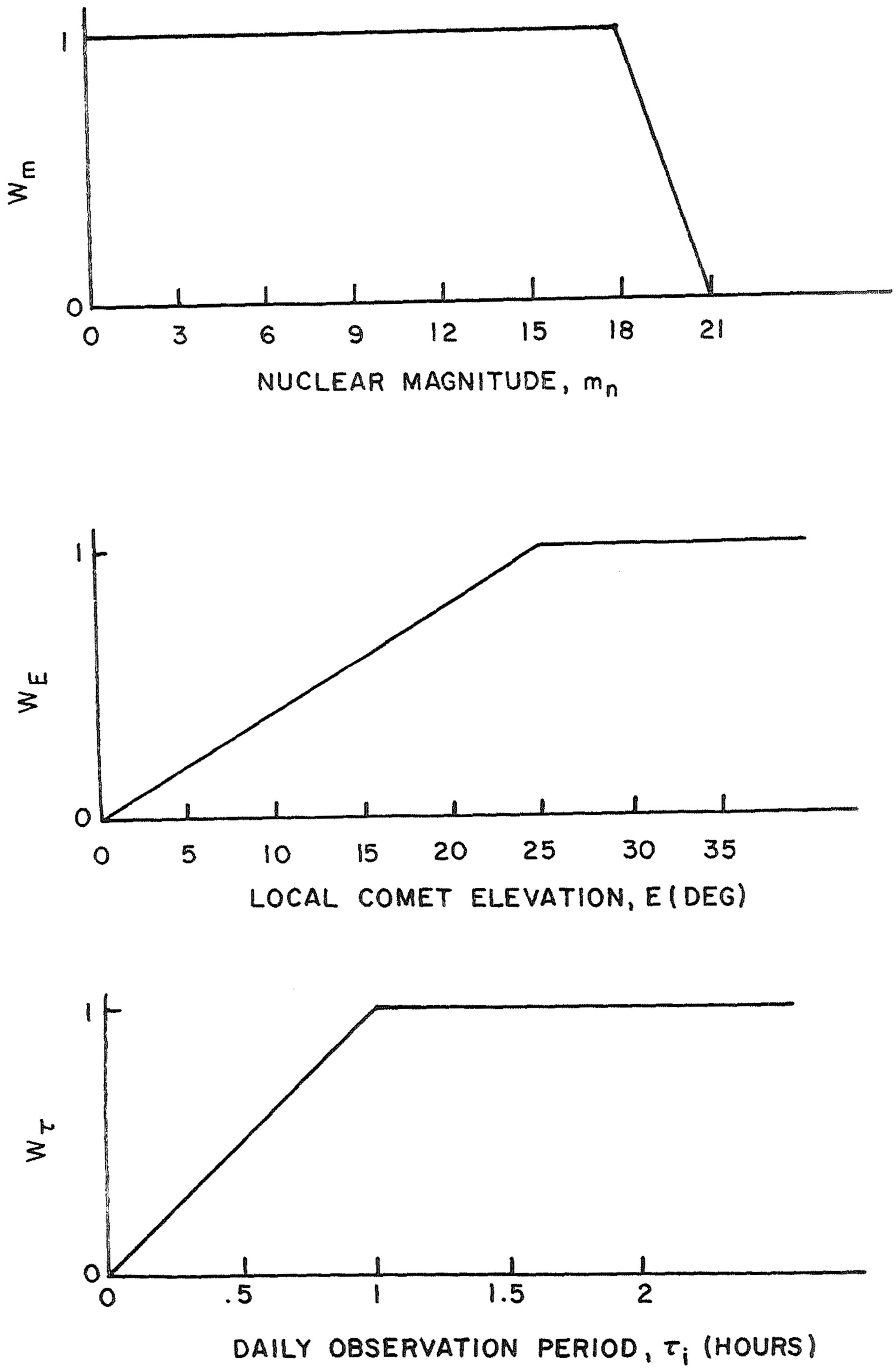

FIGURE 1. WEIGHTING FACTORS FOR EVALUATION OF EARTH-BASED OBSERVATIONS.

The total daily observation period is also considered a part of observation quality. The weighting factor W_τ (where τ is the total daily observation period) is varied from 0 to 1 as τ increases from 0 to 1 hour, and held constant at 1 for all $\tau > 1$ hour.

An accumulated performance index, P(N) is then used to combine all weighting factors with observation time to determine the history of "acceptable" observations during a comet apparition. P(N) is defined as:

$$P(N) = \sum_i W_m(i)\, W_\tau(\tau_i) \int_{\theta_s}^{\theta_r} W_E(\theta)\, d\theta,$$

$$i = -300, -299, \ldots, N(\text{days}) \qquad (3)$$

i = 0 corresponds to the date of perihelion passage and θ is the local hour angle. The gross number of observation hours on any given night, $\tau_i = \theta_r - \theta_s$, is determined from the fixed conditions that the comet be above the local horizon and the sun be at least 18° below it. $W_m(i)$ is evaluated at the beginning of the ith day.

2.4 Selection List

The accumulated performance index, P(N), and total magnitude variation (equation 2) were determined for 38 comet apparitions comprising 21 different comets. The results were applied to the sighting criteria outlined above to determine favorable apparitions for comet rendezvous missions. Each of the 21 comets considered has been observed on more than one apparition and at least three comets, Halley, Encke, and d'Arrest have been seen numerous times. Observations and selection results are presented in Table 1 which lists for each apparition the minimum geocentric distance, the values of P(-120) and P(300), the maximum brightness in total magnitudes, and the period when $m_t > 12$.

TABLE I

COMET CLASSIFICATION BASED ON EARTH RECOVERY AND SIGHTING CONDITIONS

CLASS	COMET			RECOVERY		ASTRONOMY (AFTER RENDEZVOUS)		
	YEAR	NAME	MINIMUM EARTH DISTANCE, AU	ACCUMULATED PERFORMANCE INDEX, HRS		MAXIMUM BRIGHTNESS, TOTAL MAGNITUDE	OBSERVABLE PERIOD * WHEN TOTAL MAG. < 12	
				t_p-120^d	TOTAL**		FROM	TO
GOOD	80	ENCKE	0.264	60	738	4.5	-60	-20
	82	D'ARREST	0.732	246	914	10.6	-80	50
	82	GRIGG-SKJELLERUP	0.265	521	1718	10.6	-20	40
	83	KOPFF	0.784	439	1118	9.8	-130	80
	84	ENCKE	0.647	542	1020	3.7	-40	-20
	85	GIACOBINI-ZINNER	0.479	114	1298	8.6	-70	70
	86	HALLEY	0.412	738	1856	1.5	-140	-20
							30	140
	87	BORRELLY	0.442	20	1520	9.2	-80	40
	88	TEMPLE-2	0.721	490	1125	11.8	-60	10
	91	FAYE	0.605	94	1809	11.0	-60	40
	93	FORBES	0.629	262	897	10.8	-90	40
	93	SCHAUMASSE	0.553	401	1865	9.0	-100	80
	94	TUTTLE	0.380	97	703	7.5	-70	0
	95	PERRINE-MRKOS	0.322	20	1614	11.3	-20	30
	96	KOPFF	0.593	210	1247	8.8	-110	100
	98	GIACOBINI-ZINNER	0.315	338	1210	7.8	-70	70
FAIR	80	BROOKS-2	0.960	219	1280	13.2	-	-
	80	FORBES	1.052	619	799	12.4	-	-
	81	SCHWASSMAN-WACHMANN-2	1.197	455	1703	13.0	-	-
	87	ENCKE	0.886	142	154	4.9	-	-
	87	GRIGG-SKJELLERUP	0.805	769	1269	13.1	-	-
	89	PONS-WINNECKE	1.002	689	1159	13.6	-	-
	90	ENCKE	0.703	9	359	4.8	-50	-20
	90	KOPFF	1.760	166	689	12.0	-	-
	90	TUTTLE-GIACOBINI-KRESAK	0.185	15	1429	9.7	-50	50
	92	GIACOBINI-ZINNER	2.028	137	261	11.7	-	-
	95	D'ARREST	1.711	76	100	12.7	-	-
	97	ENCKE	0.467	277	314	4.7	-	-
POOR	78	ASHBROOK-JACKSON	1.302	0	1310	11.0	-50	100
	80	TUTTLE	1.936	3	5	11.1	-	-
	81	BORRELLY	1.307	12	405	11.9	-30	10
	84	AREND-RIGAUX	0.571	0	1016	11.4	-20	60
	84	SCHAUMASSE	1.177	5	1008	10.7	-50	60
	85	HONDA-MRKOS-PAJDUSAKOVA	1.543	0	0	9.2	-	-
	86	WHIPPLE	2.176	207	905	15.6	-	-
	89	D'ARREST	1.448	1	264	12.4	-	-
	90	HONDA-MRKOS-PAJDUSAKOVA	0.179	0	150	7.8	-50	20
	92	DANIEL	1.442	0	252	16.4	-	-

* FOR A 35° NORTH LATITUDE OBSERVATORY SITE

** FOR THE PERIOD FROM t_p-300^d TO $t_p + 300^d$

The comet apparitions are categorized as Good, Fair, and Poor which is indicative of how well they satisfy the sighting criteria. The Good list contains only those apparitions which provide a recovery at least 20 days before rendezvous (i.e., 120 days before perihelion passage) and which can be observed for at least 30 days after rendezvous at total magnitudes less than 12. All 16 apparitions in the Good list have values of P(-120) (accumulated weighted observations hours) equal to or greater than 20. This means that 2-3 weeks of "acceptable" observations are available up to 120 days before perihelion. A minimum of one week following initial recovery is required to obtain enough observations to redetermine the orbit. The additional 1-2 weeks are provided as a contingency, since the interruption of observations by a bright moon in the night sky has not been considered in the observation conditions outlined above. Also all 16 comets are observable from earth at total magnitudes less than 12 for periods of 30 days or more. Halley is particularly interesting in this respect. A total of 250 days of observation are predicted, divided into two periods about perihelion, when the predicted total magnitude of the comet is less than 12.

There are 12 comets apparitions in the Fair list. Almost all of these comets have high values (> 50) of P(-120), hence providing good opportunities for recovery and tracking. Almost all of them, however, provide no opportunities for taking earth-based measurements of the comet at total magnitudes less than 12. The Encke/90 apparition has poor recovery observations, but because Encke's orbit is quite well known, and because it should be quite bright during this apparition with 30 days for earth-based observations, it was included in the Fair list. The same reasons led to the inclusion of Tuttle-Giacobini-Kresak/90 in the Fair list. Notice also the close encounter of T-G-K with the earth (Δ = 0.185 au) for this apparition.

Ten comet apparitions are in the Poor list. Half of these comets have moderately good conditions for earth-based observations during their apparitions but none (except Whipple/86) have acceptable observations for the more critical (for rendezvous) recovery and tracking criterion. Whipple is a faint comet which does not brighten much due to its large perihelion distance (2.5 au). It cannot be considered a very active comet at any time and for this reason is placed in the Poor category even though it has good recovery properties.

Supporting data is presented in the Appendix for each of the 16 comet apparitions in the Good category. Three figures and one table are included for each comet. The first two figures present earth observations data, as a function of time across the apparition, which were used for the sighting analysis. The third figure is a polar plot of the comet's orbit in the region of perihelion. A table of osculating orbit elements follows which presents future predicted element variations due to planetary perturbations only (secular variations are not included).

Since the selection process determined 16 comet apparitions, between 1975 and 2000 with good sighting characteristics it seems reasonable at this time to limit the trajectory and payload analysis to these opportunities. It is possible, of course, that some comets in the second and third sighting categories may be attractive from the standpoint of lower trajectory energy requirements. If independent results indicate this to be the case, later re-evaluation would be in order. The succeeding sections contain trajectory and payload analyses for the 16 comet apparitions with good sighting characteristics.

3. COMET RENDEZVOUS FLIGHT MODES

In this section, a number of promising comet rendezvous trajectories will be discussed with reference to their respective flight modes, which are classified according to the type of propulsion system used, i.e., ballistic or low-thrust. While trajectories may be found which use combinations of these propulsion modes, in this study, we will restrict attention to the following:

1) Multi-impulse ballistic mode
2) Gravity-assisted ballistic mode
3) Solar-electric low-thrust mode
4) Nuclear-electric low-thrust mode.

3.1 Multiple-Impulse Ballistic Mode

Considerable saving in the required velocity increment (ΔV) of ballistic comet rendezvous trajectories can be obtained by executing a mid-course plane change maneuver along the line of nodes of the comet orbit. This policy is particularly effective for missions to those comets which have high orbital inclinations. Furthermore, as total mission flight time increases towards the orbital period of the destination comet, the plane change occurs at a greater distance from the sun and, therefore, at a lower velocity. This requires a smaller velocity increment to execute the required plane change.

Missions for which the total flight time is close to the orbital period of the destination comet are particularly effective in terms of total ΔV because many of the short-period comets have lines of apsides which are close to the line of nodes and perihelion distances which are of the order of 1 au Under these circumstances, an optimum three-impulse mission begins with an initial arc which approximates the projection of the motion of the comet on the ecliptic plane and continues out to the vicinity of the comet aphelion point. Near the aphelion point, the mid-course plane change occurs so that the second arc of the trajectory is very nearly in the orbital plane of the comet and the motion closely approximates the motion of the comet. Trajectories of this description usually require the greatest velocity change at Earth departure, a modest increment at the mid-course point and a small velocity matching increment at the rendezvous point.

The multiple-impulse ballistic trajectory optimization problem (minimum ΔV) has been programmed for the UNIVAC 1108 computer. The optimization procedure begins with the specification of impulse points along the trajectory by the user. This initialization is necessary because a series of local optimum solutions exists at total flight times which differ by approximately one year. Launch and arrival points are specified in terms of time only, since the positions are given a priori as functions of time. However, the initial mid-course impulse point must be specified in terms of both time and three-dimensional position.

Next, the program connects the impulse points with conic arcs and computes the adjoint variables or Lagrange multipliers at the ends of each arc. The multipliers, along with the velocity discontinuities (impulses) at each point, are used to compute the gradient of the total ΔV over the complete trajectory with respect to the times and position components which specify the impulse points. The total ΔV which is to be minimized and its gradient are required by the search routine which uses the conjugate gradient technique to find a minimum ΔV trajectory in the vicinity of the original initialization.

Once a local optimum trajectory has been found, the computer program solves the adjoint equations and examines the magnitude of the primer vector (velocity multipliers) along each arc. The program automatically inserts additional impulses at points for which the primer magnitude is a maximum and greater than unity. After reoptimization, the new total ΔV can be compared to the previous result. In some cases the additional impulses can cause a significant reduction in total ΔV.

The comet missions are assumed to begin from a 100 nautical mile circular orbit about the earth. This is accounted for by modifying the initial values of the primer vector components (traversality condition). This initialization is detailed elsewhere (Waters, 1970) along with a complete formulation of the optimum multiple impulse ballistic trajectory problem as used in the computer program.

In this study it has been assumed that the trajectories are not strongly dependent upon vehicle configuration so that a minimum ΔV trajectory is an adequate approximation to a maximum delivered payload trajectory. Short period comet rendezvous trajectories exhibit the usual trade-off between time-of-flight and total ΔV. Furthermore, if the apsidal and nodal lines of the comet orbits nearly coincide, the minimum ΔV rendezvous trajectories have flight times which correspond closely to the periods of the comet orbits.

A further trajectory selection consideration is the distribution of velocity increments along the series of three or more impulse points. It is desirable, from a delivered payload standpoint, that most of the total velocity increment be supplied by the launch vehicle. Missions which require a post-injection velocity increment in excess of 5 km/sec are of questionable utility. With respect to the Titan 3/Centaur class of launch vehicles the velocity increment required for departure from a 100 n.m. earth parking orbit should be less than 7 to 8 km/sec, for a practical mission. The trajectories with flight times near the orbital period of the destination comet are most likely to meet these velocity increment distribution requirements because the final velocity matching increment at the rendezvous point is usually quite small.

Table 2 contains the results of a study of impulsive ballistic missions to each of the comets in the Good list of Table 1, with the exception of Halley/86. For each comet rendezvous opportunity the minimum ΔV trajectory program was initialized with a bielliptic transfer between the orbit of the earth and the comet orbit at 100 days before perihelion. The initial transfer time was taken as the orbital period of the comet plus or minus a series of one-year increments. For each case the program was allowed to iterate to the nearest minimum ΔV point.

Using Titan 3D/Centaur and Titan 3F/Centaur launch vehicle performances curves (NASA, 1970), and assuming a rendezvous stage with an I_{sp} of 400 sec, the payload delivered to the comet at rendezvous was computed for each minimum ΔV trajectory, allowing an additional 200 m/sec for guidance maneuvers. A Burner II stage was added if the resulting payload improvement was greater than 100 pounds.

Included in Table 2 are the flight time, launch date and arrival time before perihelion passage for each case studied. The impulse history is also shown along with the total velocity impulse. Trajectories with more than three impulses are included for those cases in which the total ΔV improved by more than 0.5 km/sec with added impulses. In the following subsections we will discuss those ballistic comet rendezvous missions which appear to be practical from a payload (1000 pounds) and flight time (< 5 years) standpoint and which are contained in the list of Good sighting conditions.

TABLE 2

COMET RENDEZVOUS TRAJECTORIES - IMPULSIVE BALLISTIC MODE

COMET	FLIGHT TIME (YR)	LAUNCH DATE	ARRIVAL (DAYS BP)	VELOCITY REQUIREMENT (KM/SEC) ΔV_1 *	ΔV_2	ΔV_3	ΔV TOTAL	PAYLOAD (LBS) ** TITAN 3D CENTAUR	TITAN 3F CENTAUR
ENCKE/80	2.50	3/14/78	86	5.41	4.67	2.06	12.15	60	150
P=3.30 YR.	2.71	3/8/78	15	5.43	2.26/2.45	.74	10.88	430	650
	3.53	2/20/77	97	6.09	3.56	.25	9.89	820 (BII)	1130
	4.57	2/20/76	81	6.11	3.07	1.59	10.76	520 (BII)	730
	5.63	2/14/75	67	6.43	2.97	1.74	11.14	420 (BII)	590
D'ARREST/82	2.96	8/16/79	47	6.07	2.41	2.55	11.03	440 (BII)	620
P=6.67	3.85	8/17/78	86	6.33	2.32	1.52	10.17	720 (BII)	980
	4.83	8/12/77	98	6.57	2.21	.61	9.39	1000 (BII)	1370 (BII)
	5.80	8/18/76	105	7.11	1.93	.01	9.05	1020 (BII)	1470 (BII)
	6.81	8/14/75	104	7.24	1.74	.62	9.60	800 (BII)	1190 (BII)
GRIGG-	2.92	4/28/79	45	6.12	.19/2.31	1.97	10.59	520	800
SKJELLERUP/82	3.80	4/16/78	99	6.37	2.63	1.07	10.07	760 (BII)	1020
P=4.91	4.81	4/11/77	100	6.57	2.74	.17	9.48	960 (BII)	1280
	5.78	4/26/76	98	7.03	1.75	.63	9.41	900 (BII)	1310 (BII)
KOPFF/83	1.93	8/6/81	39	4.34	2.23	4.66	11.23	150	280
P=6.31	2.90	7/25/80	62	5.28	1.86	2.61	9.74	880	1250
	3.86	7/16/79	85	5.84	1.70	1.41	8.95	1200	1740
	4.78	7/14/78	115	6.22	1.50	.79	8.51	1470 (BII)	1970
	5.83	7/3/77	106	6.41	.30/1.30	.26	8.27	1570 (BII)	2080
	6.81	7/7/76	110	6.78	1.34	.86	8.97	1130 (BII)	1580 (BII)
ENCKE/84	2.76	3/13/81	100	5.59	4.23	1.10	10.92	420	640
P=3.30	3.82	2/26/80	97	5.97	3.98	.58	10.02	770 (BII)	1070
	4.98	2/26/79	37	6.34	2.82	1.30	10.45	610 (BII)	850
GIACOBINI-	4.65	10/5/80	96	6.57	3.61	.87	11.05	450 (BII)	640 (BII)
ZINNER/85	5.64	9/29/79	107	6.65	3.36	.70	10.71	540 (BII)	760 (BII)
P=6.41	6.60	10/9/78	111	7.20	2.82	.85	10.87	460 (BII)	700 (BII)
BORRELLEY/87	4.77	12/3/82	96	6.59	3.67	.82	11.08	440 (BII)	620 (BII)
P=7.02	5.74	12/6/81	103	6.68	3.45	.19	10.31	650 (BII)	920 (BII)
	6.73	12/9/80	104	6.95	3.12	.63	10.70	520 (BII)	760 (BII)
TEMPLE-2/88	2.91	8/2/85	73	5.75	1.56	2.63	9.94	700	1130
P=5.26	3.86	8/1/84	96	6.24	1.43	1.55	9.23	1110 (BII)	1490
	4.87	7/19/83	104	7.10	1.34	.25	8.69	1165 (BII)	1700 (BII)
	5.87	7/22/82	101	6.82	1.39	.77	8.98	1120 (BII)	1600 (BII)
FAYE/91	4.78	10/30/86	95	6.00	1.91/.39	.08/1.21	9.59	950 (BII)	1310
P=7.38	5.77	10/28/85	102	6.24	1.09/1.21	.04/.69	9.27	1090 (BII)	1460
	6.68	10/30/84	133	6.55	.89/1.12	.23/.05	8.85	1240 (BII)	1690 (BII)
FORBES/93	2.50	8/6/90	64	5.03	1.40	3.78	10.20	670	960
P=6.42	3.32	8/0/89	138	5.66	.92	2.69	9.27	1070	1550
	4.42	7/20/88	109	6.04	.63/.07	1.92/.10	8.77	1340 (BII)	1830
	5.41	7/11/87	122	6.34	.65/.51	1.18	8.67	1360 (BII)	1810
	6.40	6/26/86	111	6.47	1.35/.51	.30/.33	8.95	1200 (BII)	1600
SCHAUMASSE/93	4.76	2/9/88	114	5.95	1.63	.61/2.22	10.42	580	900
P=8.18	5.78	2/2/87	113	6.15	2.14/.01	.58/1.08	9.96	880 (BII)	1201
	6.80	1/30/86	108	6.38	2.34/.02	.52/.35	9.61	990 (BII)	1240
TUTTLE/94	6.17	1/8/88	109	6.42	6.99/.02	3.77	17.2	NO PRACTICAL CASES FOUND	
P=13.61									
PERRINE-	2.82	11/24/92	55	5.88	2.32	2.74	10.94	420	650
MRKOS/95	3.76	11/14/91	87	6.17	2.26	1.67	10.10	750 (BII)	1030
P=6.71	4.72	11/19/90	99	6.57	1.98	1.02	9.57	930 (BII)	1280 (BII)
	5.70	11/16/89	109	6.72	1.34/.81	.06	8.92	1160 (BII)	1620 (BII)
	6.73	11/11/88	104	6.82	.02/1.07	1.04/.21	9.17	790 (BII)	1040 (BII)
KOPFF/96	2.51	8/0/93	60	5.01	1.99	3.04	10.05	740	1060
P=6.31	3.50	7/21/92	75	5.66	1.78	1.63	9.07	1170	1680
	4.48	7/12/91	93	6.07	1.68	.81	8.56	1452 (BII)	1970
	5.45	7/13/90	100	6.43	1.55	.43	8.42	1480 (BII)	1970
	6.45	7/10/89	103	6.67	1.40/.21	.36	8.64	1312 (BII)	1810
GIACOBINI-	3.66	10/9/94	31	6.27	4.25	1.51	12.02	160	300
ZINNER/98	4.49	10/6/93	95	6.49	3.73	.97	11.19	410 (BII)	570
P=6.41	5.45	10/9/62	109	6.83	3.34	.42	10.58	560 (BII)	810 (BII)
	6.46	10/4/91	108	6.88	2.45/.88	.22	10.43	600 (BII)	870 (BII)

* Departure from 100 nautical mile earth orbit; $\Delta V_1 = V_C - 25{,}581$, ft/sec

** $\Delta V_2 + \Delta V_3$ + 200 m/sec (guidance) imparted by single stage, I_{sp} = 400 sec

3.1.1 Encke/80 Opportunity

The 3.5-year mission to Encke/80 (Table 2) has a payload capability of 820 pounds with a Titan 3D/Centaur/Burner II launch vehicle. It is a marginal mission. However, with the use of a Titan 3F/Centaur configuration, 1130 pounds can be delivered, representing an acceptable opportunity. This mission will be described in detail because of the considerable scientific interest in Encke. The relatively short orbital period (3.3 years) of Comet Encke suggests the possibility of a series of missions at successive apparitions or perhaps a station-keeping mission through one complete orbital period. It should also be noted that mission analysis for the Encke/80 apparition also applies for Encke/90. Three orbital periods (9.9 years) very nearly equals ten years so that the earth-based positions are nearly identical.

The spacecraft trajectory for the 3.5-year mission to Comet Encke is illustrated in Figure 2. Note that the second leg of the trajectory closely approximates the path of the comet, resulting in the small velocity increment requirement at the rendezvous point. This plot also shows the substantial change in eccentricity which is required at mid-course to match the orbit of Encke. It is this effect which limits the payload capability.

The best arrival date for the 3.5-year ballistic mission occurs 97 days before perihelion passage. The data of Figure 3 indicates, however, that useful payloads can be delivered at from 50 to more than 200 days before perihelion passage with a Titan 3F/Centaur launch vehicle if a marginal 800-lb. payload capability is acceptable. There are 40 days available during the comet's apparition for earth-based observations.

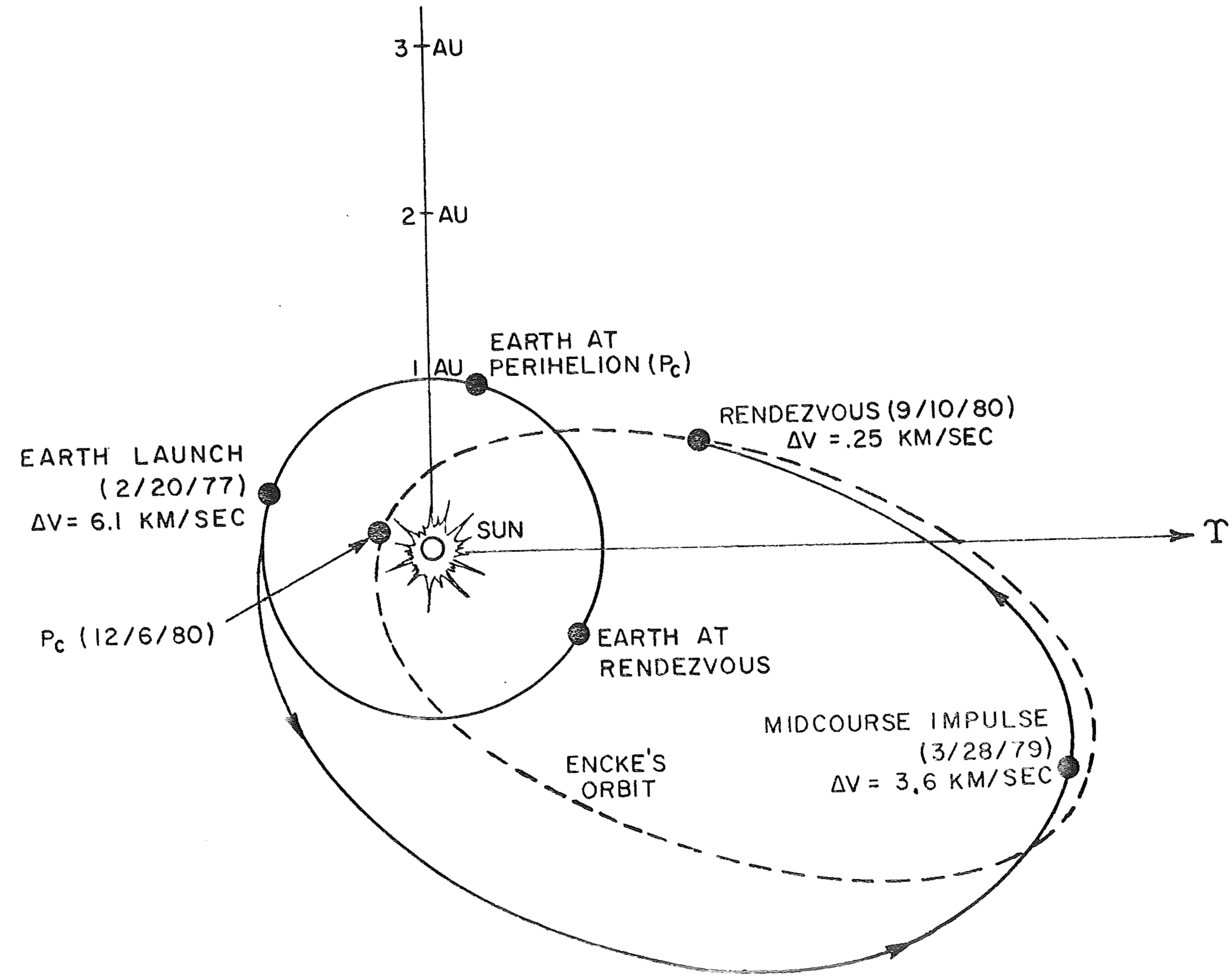

FIGURE 2. 1290-DAY THREE-IMPULSE MISSION TO COMET ENCKE/80

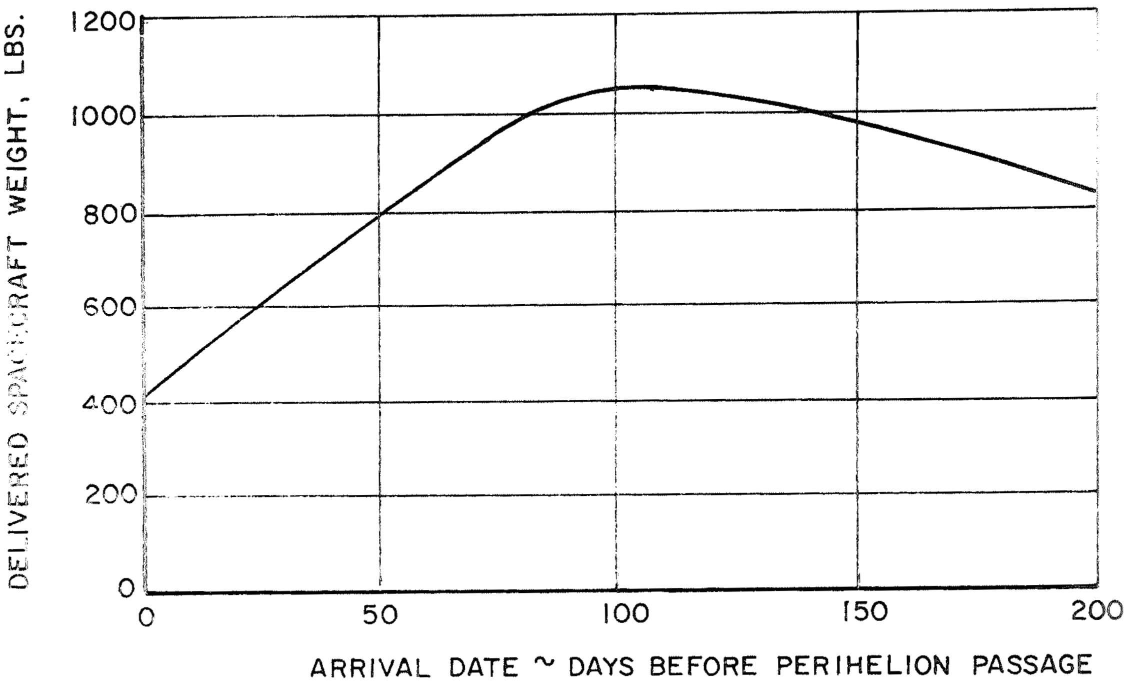

FIGURE 3. EFFECT OF ARRIVAL DATE ON DELIVERED PAYLOAD AT ENCKE/80 (TITAN 3F/CENTAUR)

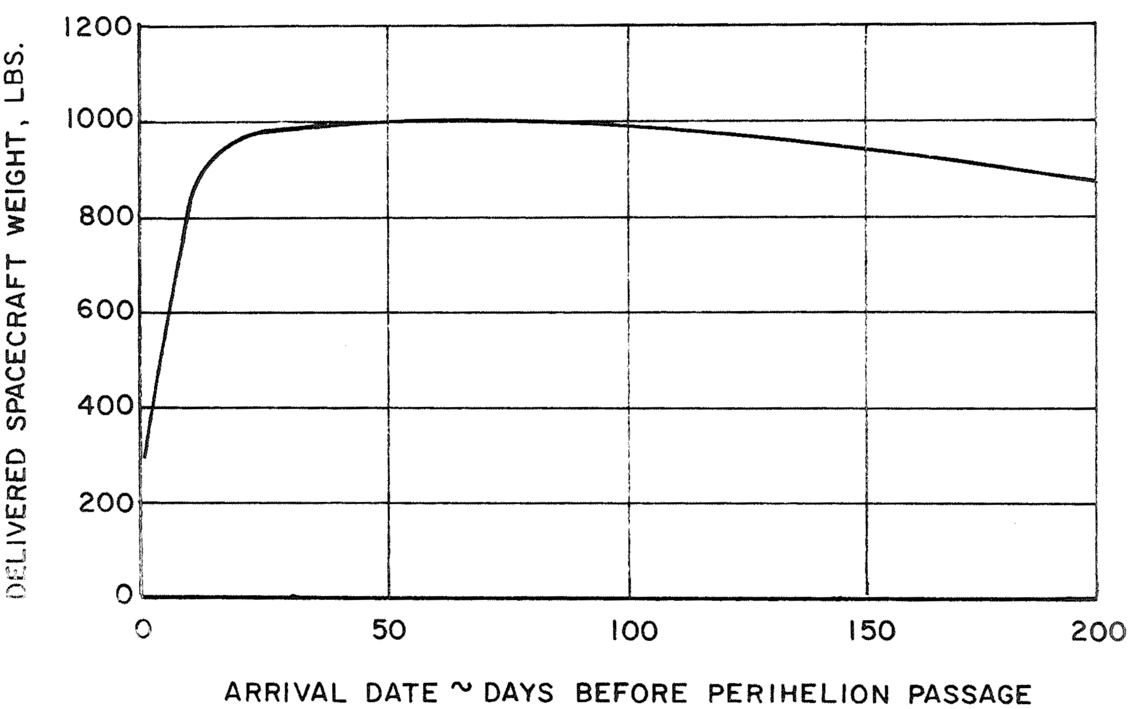

FIGURE 4. EFFECT OF ARRIVAL DATE ON DELIVERED PAYLOAD AT D'ARREST/82 (TITAN 3F/CENTAUR)

3.1.2 d'Arrest/82 Opportunity

The 3.85-year mission to d'Arrest/82 is similar to the Encke/80 mission in terms of deliverable payload. However, by increasing flight time by one year, (launch in August, 1977), a 15-20 percent increase in payload is obtained with a 4.8-year flight time.

The 4.8-year mission arrives 98 days before perihelion passage, but as in the Encke/80 case, the arrival time can fall between 20 and more than 200 days before perihelion passage for an 800-lb. rendezvous payload capability (see Figure 4). Earth-based observations of d'Arrest at brighter than 12th magnitude (total) are predicted for a period of 130 days.

The 4.8-year trajectory to d'Arrest/82 is shown in Figure 5 and will be compared later with a similar gravity-assisted mission.

3.1.3 Grigg-Skjellerup/82 Opportunity

The 4.8-year transfer has a payload capability of 960 pounds using the Titan 3D/Centaur/BII. There are 60 days of earth observations possible following rendezvous at 100 days before perihelion. To raise the payload above 1000 pounds and simultaneously reduce the flight by one year a Titan 3F/Centaur launch vehicle is required. Without it this mission is judged to be of only moderate interest.

3.1.4 Kopff/83 Opportunity

This is one of the more attractive ballistic mission possibilities. A 1000 pound payload is deliverable on a flight of less than 4 years using a Titan 3D/Centaur launch vehicle. With over 400 hours available for comet tracking before the

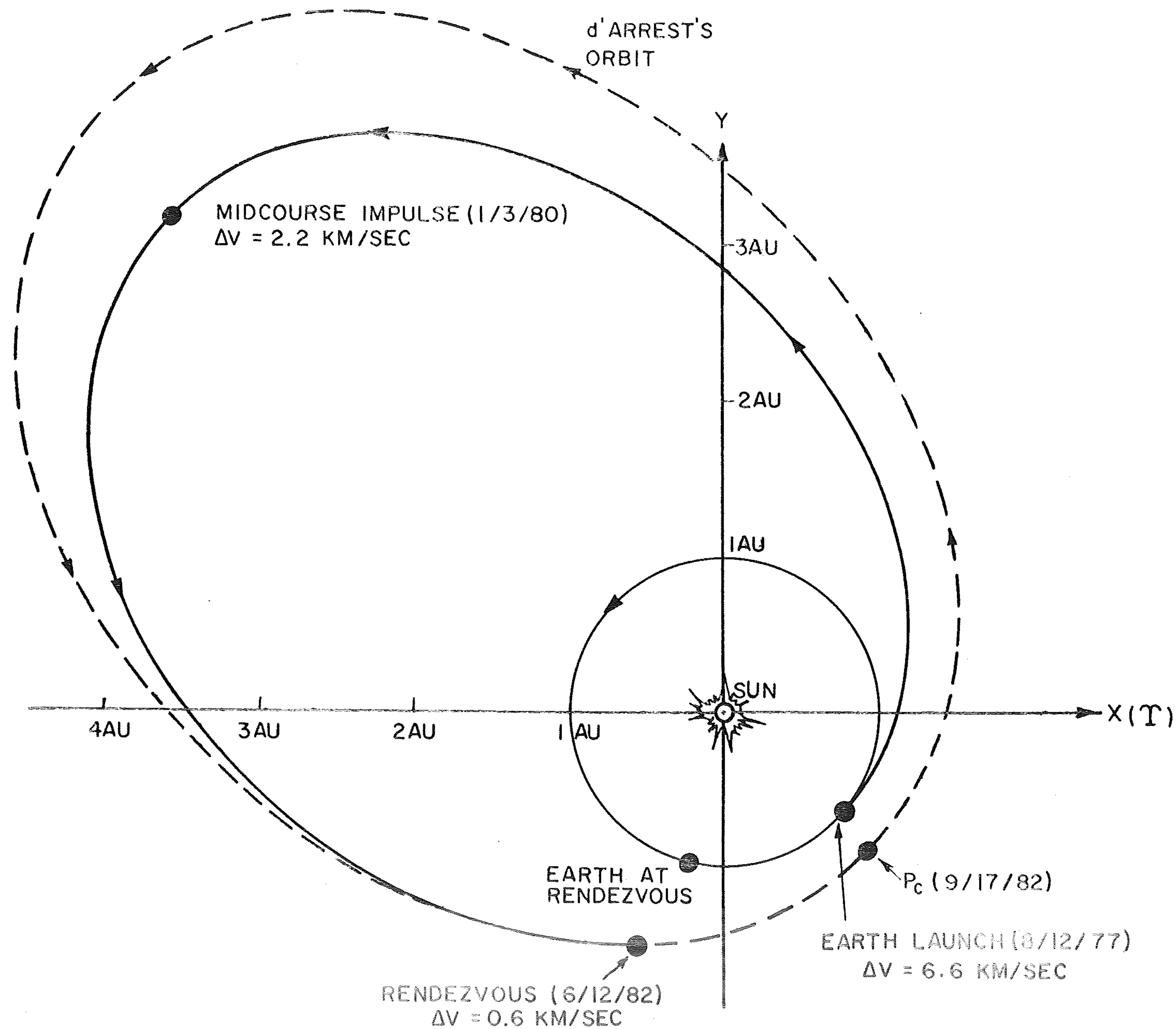

FIGURE 5. 4.8-YEAR THREE-IMPULSE RENDEZVOUS WITH COMET D'ARREST/82

rendezvous date, spacecraft guidance should not be difficult. A total of over 200 days for earth-based observations is available during this apparition with 165 of these occurring after rendezvous.

3.1.5 Encke/84 Opportunity

As with the Encke/80 opportunity a Titan 3F/Centaur launch vehicle is required to deliver at least 1000 pounds payload. This opportunity has somewhat better sighting characteristics for recovery than the 1980 opportunity but only 20 days are predicted for earth-based observations at less the 12th magnitude.

3.1.6 Temple-2/88 Opportunity

The maximum deliverable payload of over 1100 pounds in less than a 4 year flight time makes this opportunity comparable with that of Kopff/83. The total effective observation time is 70 days as compared with 200 days for Kopff/83.

3.1.7 Faye/91 Opportunity

This mission would require a flight time of nearly 6 years to deliver a 1000 pound payload with a Titan 3D/Centaur launch vehicle. There are 100 days for earth-based observation. The long flight time required to attain 1000 pounds payload is the main drawback to this opportunity.

3.1.8 Forbes/93 Opportunity

In terms of flight time and payload this is one of the best ballistic mission opportunities, requiring a 3.3-year flight time to deliver a 1000 pound payload with a Titan 3D/Centaur launch vehicle. There are 262 hours for recovery and tracking prior to rendezvous. The earth-based observation period extends for 130 days, which is about average. Programmatically, however, post-1990 launch opportunities must be regarded as of little current planning interest.

3.1.9 Perrine-Mrkos/95 Opportunity

With an observation time of only 50 days and 5.7 years required to deliver a 1000 pound payload with a Titan 3D/Centaur launch vehicle, this is by comparison a marginal mission opportunity.

3.1.10 Kopff/96 Opportunity

Results obtained during a study of ballistic missions to Kopff/96 are very similar to those obtained for the Kopff/83 case, although the flight time is 0.6 years longer. From payload and observation standpoint both mission opportunities to Kopff are attractive.

3.1.11 Summary of Practical Multi-Impulse Missions

Ballistic multi-impulse missions delivering more than 1000 pounds payload to rendezvous using Titan 3/Centaur launch vehicles (D or F versions) are summarized in Table 3. In all cases rendezvous occurs no later than 80 days before perihelion. On a comparative basis, missions to Kopff/83, Temple-2/88, and Forbes/93 have the best payload/flight time characteristics. All have payload capabilities in excess of 1000 pounds with the smaller Titan 3D/Centaur vehicle and all have flight times of less than 4 years. Missions to d'Arrest/82 and Kopff/96 have comparable payload capabilities, but the flight times are in the range 4-5 years. The remaining opportunities require the larger Titan 3F/Centaur to achieve at least 1000 pounds of rendezvous payload.

TABLE 3

SUMMARY OF ACCEPTABLE MULTI-IMPULSE RENDEZVOUS OPPORTUNITIES

COMET/APPARITION	LAUNCH DATE	TRIP TIME (YRS.)	ARRIVAL DATE (DBP)*	RENDEZVOUS PAYLOAD (LBS.)	
				TITAN 3D CENTAUR	TITAN 3F CENTAUR
ENCKE /80, 90	2/20/77	3.53	97	820+	1130
d' ARREST /82	8/12/77	4.83	98	1000+	1370+
GRIGG-SKJELLERUP/82	4/16/78	3.80	99	760+	1020
KOPFF /83	7/16/79	3.86	85	1200	1740
ENCKE/84	2/26/80	3.82	97	770+	1070
TEMPLE -2/88	8/1/84	3.86	96	1110+	1490
FAYE/91	10/30/86	4.78	95	950+	1310
FORBES /93	7/31/89	3.32	138	1070	1550
PERRINE - MRKOS / 95	11/14/91	3.76	87	750+	1030
KOPFF / 96	7/12/91	4.48	93	1452+	1970

* DAYS BEFORE PERIHELION

+ BURNER II REQUIRED

From a trajectory analysis standpoint, it is interesting to note that the orbits of the comets, for which effective payload delivery was obtained, have several features in common. The following partial list of orbital elements illustrates this.

Comet	P	e	Ω	ω	i
Encke	3.3	.85	334°	186°	12°
d'Arrest	6.67	.6	143°	174°	18°
Kopff	6.63	.56	121°	162°	5°
Temple-2	5.26	.55	119°	191°	13°
Forbes	6.42	.55	25°	260°	5°

With the exception of Forbes, each comet orbit has an argument of perihelion, ω, near 180 degrees so that the plane change can be accomplished at the economical aphelion point. In the case of Forbes (and to a lesser extent also Kopff) the fact that the apsidal line is not at 180° from the nodal crossing is offset by an inclination angle which is considerably smaller than average. The list also shows that the eccentricities are nearly identical with the exception of Encke. The combination of short-period, high eccentricity and moderate inclination make Encke a more difficult comet for ballistic rendezvous with acceptable payload.

In summary, a number of acceptable ballistic rendezvous missions to the periodic comets have been identified. However, the results show that flight times of about four years are required. In an effort to reduce flight time, increase payload, and add more acceptable opportunities, other propulsion modes were investigated and are reported in the following subsections.

3.2 Gravity-Assisted Ballistic Mode

Jupiter-assisted trajectories can be useful in reducing the total ΔV requirement of 3-impulse ballistic comet rendezvous missions. Michielsen (1968) has presented several special cases for a Halley rendezvous mission including Saturn-assisted trajectories. Unfortunately, the positions of Jupiter and Saturn are not ideal for a Halley/86 rendezvous mission and the resulting flight time and launch vehicle requirements are excessive (see review in section 3.2.4).

There should exist, however, other comet rendezvous opportunities for which a Jupiter-assist provides a significant improvement in payload capability. In conducting a preliminary search for such opportunities the following guidelines were helpful:

1. The position of Jupiter should lie near the comet's line of apsides (orbit axis line) at the time that the comet is at its aphelion point;
2. The comet's aphelion distance should be commensurate with Jupiter's orbital radius (if the aphelion distance is beyond Jupiter, it is best that the comet leads Jupiter in longitude at the time of aphelion, if the aphelion distance is within Jupiter's orbit the comet should lag Jupiter);
3. For comets of high inclination, Jupiter's position at the time of swingby should lie near the comet's orbital plane (A favorable condition, then, is when the comet's line of nodes is near the line of apsides, and fortunately, this condition is met by a large number of comets).

These guidelines were applied to all 38 comet apparitions considered in the sighting analysis. It was anticipated that the guidelines would be sufficiently restrictive to eliminate the majority of these apparitions and therefore consideration was not limited to the 16 apparitions in the category of Good sighting characteristics. Most of the candidate comets failed to meet the first guideline of commensurate longitudes. Seven comet opportunities are presented in Table 4, covering the period 1975-1990 (for which reliable comet orbit data was available) which appear to be potentially good candidates for the Jupiter-assisted rendezvous flight mode. Their longitudinal positions at aphelion relative to Jupiter are presented in polar coordinates in Figure 6. These selections are based on a somewhat arbitrary criterion that the longitude difference between the comet (at aphelion) and Jupiter be less than 45°. Note that the second guideline outlined above is satisfied by only three of the seven comets -- d'Arrest/82, Honda-Mrkos-Padjuskova/85, and Tuttle-Giacobini-Kresak/90. Although T-G-K/90 doesn't satisfy the third guideline very well, the relatively low inclination of its orbit (10°) was a mitigating factor in its selection.

A search of Jupiter gravity-assisted trajectories for each of the seven comet apparitions in Table 4 was performed to determine favorable ΔV requirements for rendezvous. The SPARC Computer Program (Joseph and Richard, 1966) was used to generate the trajectories. A network of trajectories were computed by first selecting a near-optimum launch date for the earth-Jupiter transfer for a range (~ 500 days) of Jupiter arrival dates around the comet's aphelion date. The program has the capability of automatically determining all possible Jupiter-comet transfers (and associated Jupiter flyby geometry) for a specified Jupiter arrival date. By varying the arrival date at Jupiter over the range of interest a spectrum of gravity-assisted trajectories to

TABLE 4

JUPITER GRAVITY-ASSIST OPPORTUNITIES FOR COMET RENDEZVOUS

COMET/APPARITION	APHELION DISTANCE (AU)	INCLINATION (DEG)	LONGITUDE OF NODE (DEG)	COMET LONGITUDE AT APHELION (DEG)	JUPITER LONGITUDE AT COMET APHELION DATE (DEG)
d'ARREST/82	5.6	20	139 (AN)*	145	142
HONDA-MRKOS-PADJUSKOVA/85	5.5	8	227(AN)	237	227
GIACOBINI-ZINNER/85	6.0	32	195(AN)	190	217
WHIPPLE/86	5.3	10	183(AN)	204	225
BORRELLY/87	5.9	30	255(DN)	248	285
ENCKE/87	4.1	12	334(AN)	335	321
TUTTLE-GIACOBINI-KRESAK/90	5.2	10	333(DN)	23	10

* AN: ASCENDING NODE
DN: DESCENDING NODE

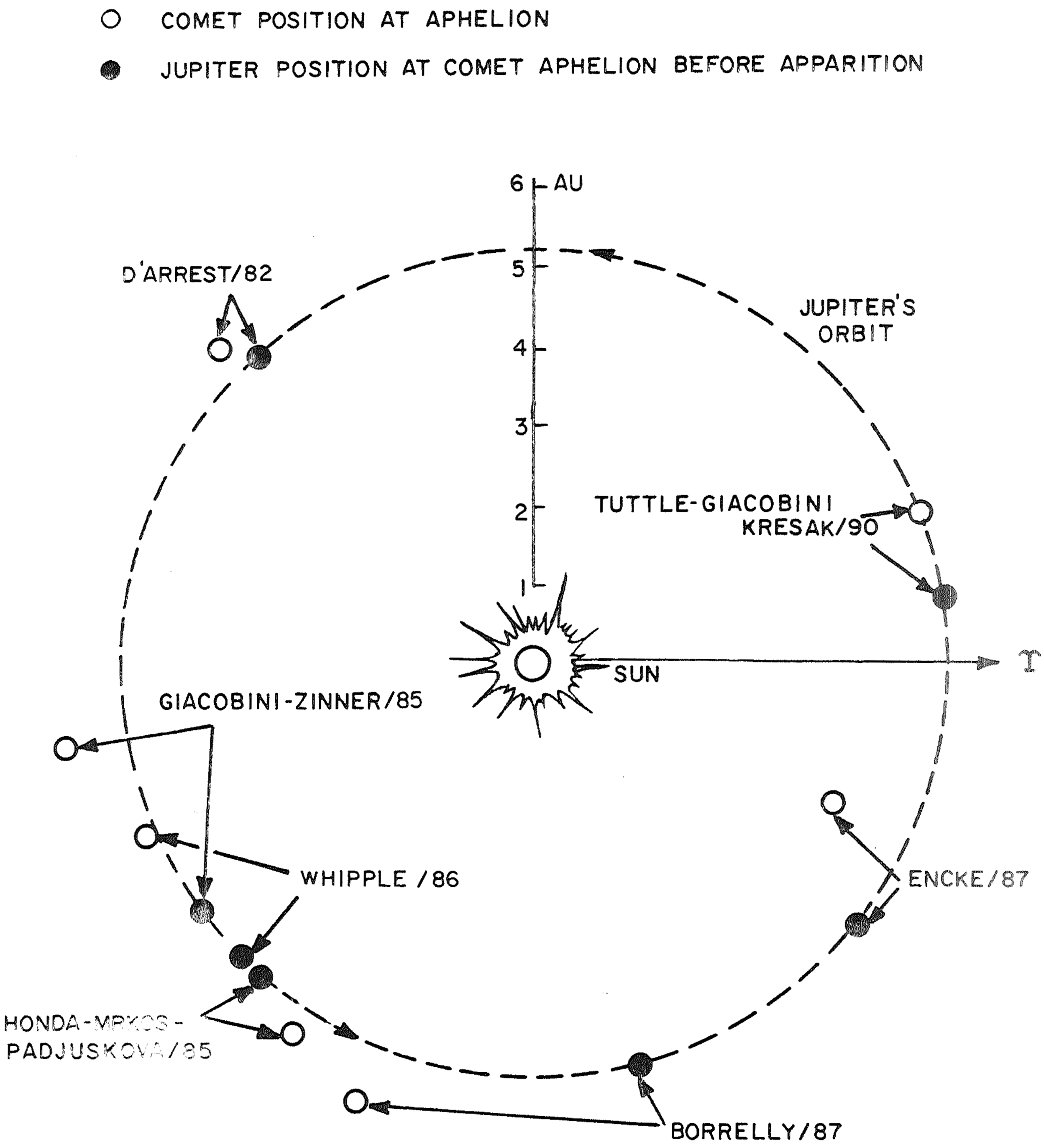

FIGURE 6. JUPITER GRAVITY-ASSIST OPPORTUNITIES
FOR COMET RENDEZVOUS

the comet was generated. In general, Type I-Class 1 post-Jupiter transfers were selected for payload analysis since these are the ones which intercept the comet before perihelion and have relatively low approach velocities.

Performance results for each of the seven comet apparitions are presented in Table 5. A 400-sec I_{sp} space-storable braking propulsion system has been assumed and an allowance of 200 m/sec for mid-course guidance was included in the payload determination. Rendezvous times other than 100 days before perihelion are a reflection of a compromise between sighting requirements and payload capability. Only four of the seven comets listed can be reached with more than a 1000 pound spacecraft using Jupiter gravity assist.

Of the four Jupiter-assisted comet rendezvous missions with payload capability greater than 1000 pounds only the d'Arrest/82 mission is in the Good category of sighting criteria. H-M-P/85 and Whipple/86 apparitions are both in the Poor category. H-M-P/85, however, has very low energy requirements and two launch opportunities in successive years are possible (if the larger Titan 3F is available). Whipple/86 on the other hand, is a mission which, in addition to poor sighting characteristics, requires a large two-stage capture maneuver to attain rendezvous with more than 1000 pounds, provided the Titan 3F/Centaur/Burner II is used. The T-G-K/90 apparition is in the fair category. It has poor recovery characteristics for an arrival date 150 days before perihelion. Earth-based observations are, however, fairly good with 100 days viewing at less than 12th magnitude predicted. Mission and trajectory characteristics are discussed in more detail in the following subsections for the d'Arrest/82, H-M-P/85, T-G-K/90 and Halley/86 gravity-assisted rendezvous missions.

TABLE 5

PAYLOAD SUMMARY OF JUPITER-ASSISTED COMET RENDEZVOUS OPPORTUNITIES

COMET / APPARITION	LAUNCH DATE	CLOSEST APPROACH AT JUPITER (R_J)	TRIP TIME (YRS)	ARRIVAL DATE (DBP)	RENDEZVOUS PAYLOAD (LBS)	
					TITAN 3D CENTAUR BURNER II	TITAN 3F CENTAUR BURNER II
d' ARREST /82	9/13/77	72.8	4.68	100	1040	1430
HONDA-MRKOS-PADJUSKOVA/85	12/16/80 12/31/81	54.8 7.5	4.16 3.12	100 100	1815 760	2480 1060
GIACOBINI-ZINNER/85	11/2/79	53.1	5.27	200	440*	620*
WHIPPLE/ 86	1/1/82	15.8	4.18	100	800*	1110*
BORRELLY /87	12/16/80 12/31/80	81.3 71.5	6.45 5.53	200 150	460* 440*	645* 620*
ENCKE /87	5/10/84	8.2	3.08	100	90*	140*
TUTTLE-GIACOBINI-KRESAK / 90	5/14/85	>150	4.50	150	750	1075

* TWO-STAGE RENDEZVOUS MANEUVER

3.2.1 d'Arrest/82 Opportunity

d'Arrest/82 is a particularly interesting candidate for a Jupiter-assisted rendezvous mission because of its favorable phasing with Jupiter and "Good" sighting characteristics. Also, this mission, if attractive, could have an immediate impact on advanced mission plans which currently include a flyby mission to d'Arrest in 1976.

Trajectory search results suggest that Type I, Class 1 transfers after Jupiter-assist provide the best mission characteristics. Approach velocities are low and rendezvous occurs before perihelion, in time to perform "in situ" measurements during the comet's period of maximum activity. Several important mission parameters for these trajectories are presented as a function of rendezvous time before perihelion in Figure 7.

Two payload curves are shown, the lower one for Titan 3D/Centaur/Burner II launches, the upper one for Titan 3F/Centaur/Burner II launches. Payload is defined as net weight (rendezvous retro stage not included) delivered to the comet. A space-storable retro propulsion system (I_{sp} = 400 sec) has been assumed with a built-in allowance of 200 m/sec for trajectory control. The net payloads reach their maximum values, 1330 and 1820 pounds, respectively, between 400 and 500 days before perihelion, where the comet approach velocity is minimum at about 1.65 km/sec.

The total flight time obviously approaches the time between launch and d'Arrest's perihelion (about 5 years) as the rendezvous time before perihelion approaches zero. Nuclear magnitude (for recovery and tracking) and total magnitude (for earth-based observations) are shown in the top graph of Figure 7. The distance of closest Jupiter approach is very large for the

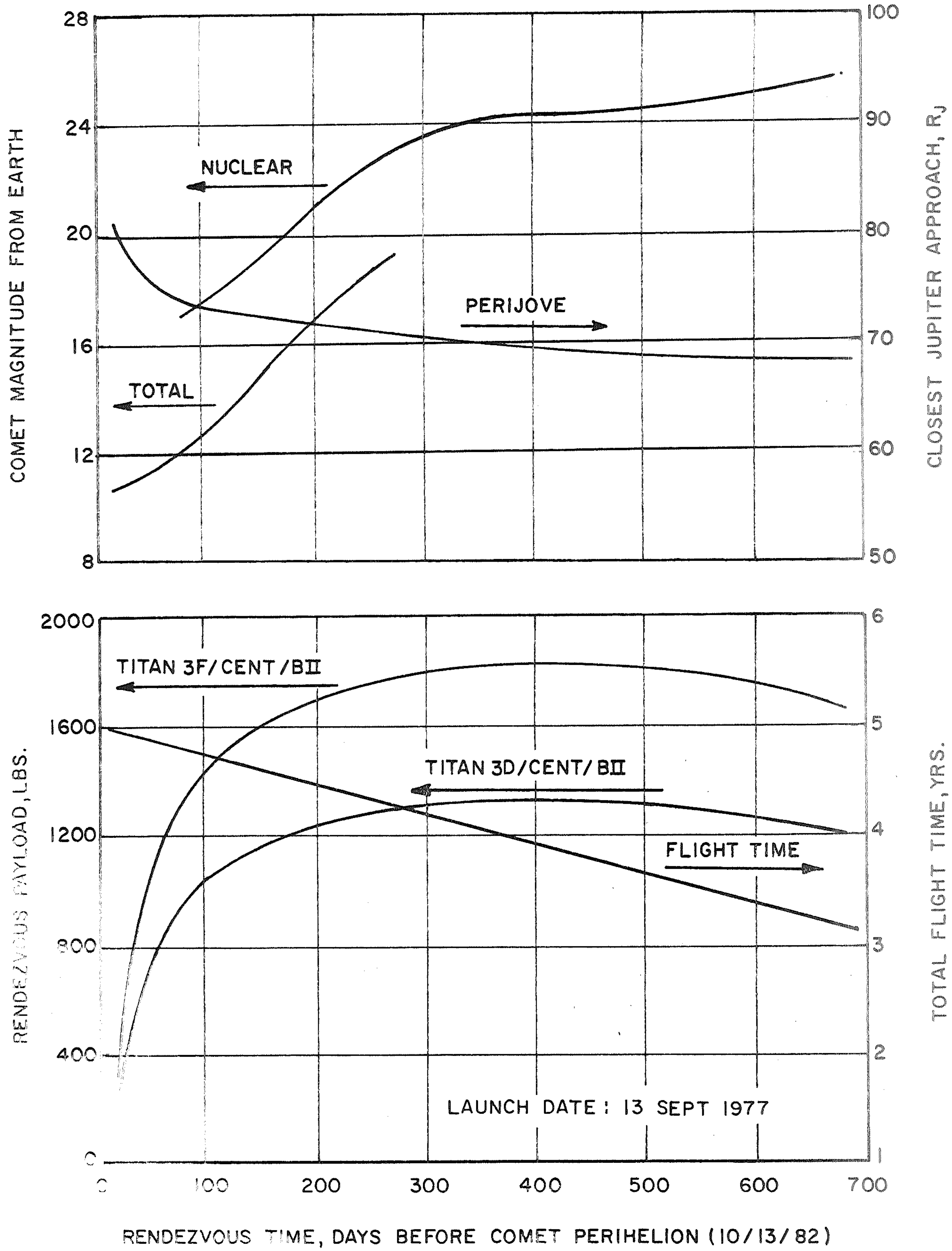

FIGURE 7. JUPITER-ASSISTED COMET D'ARREST/82 RENDEZVOUS MISSION PARAMETERS

rendezvous times considered.

If earth-based recovery and tracking are important to the final rendezvous maneuver, the arrival time would probably be delayed beyond the peak payload point (about 450 days before perihelion). Rendezvous could be as late as 100 days before perihelion and there would still be sufficient net payload using the Titan 3D/Centaur/Burner II (1040 lbs).

A Jupiter-assisted trajectory for rendezvous with d'Arrest at 123 days before perihelion was chosen from Figure 7 as an illustration of an acceptable mission profile. Pertinent mission characteristics are presented in Table 6. The Titan 3D/Centaur/Burner II launched payload of 1100 pounds should be adequate to perform a comprehensive rendezvous investigation of d'Arrest. A polar plot of the trajectory projected in the ecliptic plane is presented in Figure 8. Positions of the earth are shown at various critical points in the mission. The plot implies that d'Arrest passes near Jupiter before rendezvous. This is in fact the case, so the post-assist rendezvous trajectory is based on the perturbed comet elements due to this near encounter. The earth is in a very favorable position for earth-based comet orbit determination prior to rendezvous. This may not be true for an on-board optical tracking system since the plot also implies a spacecraft approach from behind the comet with respect to the sun.

3.2.2 Honda-Mrkos-Pajduskova/85 Opportunities

H-M-P/85 is a "poor" apparition for recovery, tracking, and earth-based observation because of unfortunate earth-comet geometry at this time. On the other hand, H-M-P's phasing with

TABLE 6

COMET d'ARREST/82

JUPITER-ASSISTED RENDEZVOUS MISSION EXAMPLE

Launch Date	13 Sept. 1977
Characteristic Velocity, ft/sec	48070
Injected Weight, lbs.	
Titan 3D/Centaur/Burner II	2525
Titan 3F/Centaur/Burner II	3430
Swingby Date	17 Sec. 1979
Hyperbolic Jupiter Approach Velocity, km/sec	6.04
Radius of Closest Approach, Jupiter Radii	72.8
Arrival Date	18 May 1982
Arrival, Days Before Perihelion	122.6
Comet Brightness	
Nuclear Magnitude	18.2
Total Magnitude	13.6
Distance From Earth, AU	0.99
Distance From Sun, AU	1.89
Intercept Velocity, km/sec	2.155
Guidance ΔV Allowance, km/sec	0.200
Rendezvous Payload, lbs.*	
Titan 3D/Centaur/Burner II	1110
Titan 3F/Centaur/Burner II	1530
Flight Time to Rendezvous, Years	4.68

* Retro Stage Propellant is Space-Storable at 400 sec I_{sp}

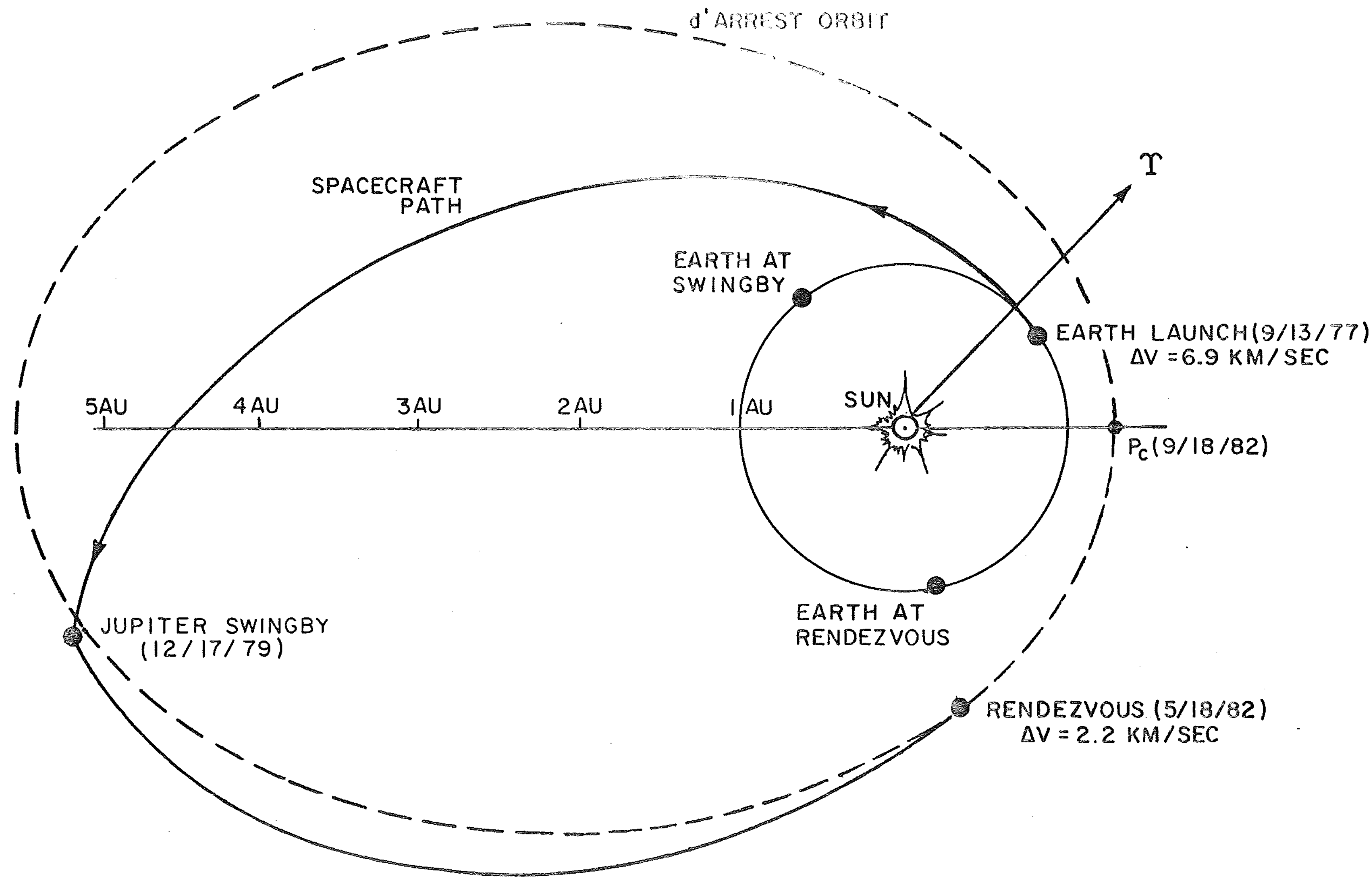

FIGURE 8. 4.7-YEAR JUPITER GRAVITY-ASSISTED MISSION TO D'ARREST/82

Jupiter results in the best payload capability of all the gravity-assisted rendezvous missions considered. There are also two reasonable launch opportunities for the mission which occur in 1980 and 1981.

For these reasons, a brief summary of characteristics for two Jupiter-assisted rendezvous missions with H-M-P are presented in Table 7. Both trajectories have the same arrival date, 100 days before perihelion, but the payload capabilities, and Jupiter swingby conditions are quite different. The payload capability with the Titan 3D/Centaur/Burner II is more than adequate (1815 pounds) for the '80 opportunity. For the '81 opportunity the Titan 3F/Centaur/Burner II would be necessary to provide at least 1000 pounds net payload. Although the '81 opportunity has considerably less payload capability a back-up opportunity is a positive factor for mission-planning. The flight time is one year shorter at 3.1 years for the '81 opportunity and the Jupiter passage distance is much closer than for the '80 opportunity, decreasing from 55 R_j to 7.5 R_j. Unfortunately, computer data for H-M-P/85 showed an accumulated observational performance index of P = 0 hours (see Table 1), for the entire apparition, confirming the suspected poorness of sighting conditions.

3.2.3 Tuttle-Giacobini-Kresak/90 Opportunity

Mission parameters, varying as a function of rendezvous time before perihelion are presented for T-G-K/90 in Figure 9. As with d'Arrest/82, payload capability (shown for both Titan launch vehicles) rises to a maximum several hundred days before perihelion and then falls off rapidly as the comet approach velocity increases. The rapid increase in rendezvous ΔV as the comet approaches perihelion is caused by small differences between the comet's and spacecraft's orbital planes combined with their high velocities near perihelion. For T-G-K/90 this

TABLE 7

COMET HONDA-MRKOS-PADJUSKOVA/85

JUPITER-ASSISTED RENDEZVOUS MISSION EXAMPLE

Launch Date	16 Dec. 1980	31 Dec. 1981
Characteristic Velocity, ft/sec	48400	47780
Injected Weight, lbs.		
Titan 3D/Centaur Burner II	2405	2635
Titan 3F/Centaur/Burner II	3270	3580
Swingby Date	23 Jan. 1983	22 Sept. 1983
Hyperbolic Jupiter Approach Velocity, km/sec	7.06	9.72
Radius of Closest Approach, Jupiter Radii	54.8	7.5
Arrival Date	13 Feb. 1985	13 Feb. 1985
Arrival, Days Before Perihelion	100	100
Comet Brightness		
Nuclear Magnitude	23.3	23.3
Total Magnitude	19.3	19.3
Distance From Earth, AU	2.65	2.65
Distance From Sun, AU	1.75	1.75
Intercept Velocity, km/sec	0.628	3.196
Guidance ΔV Allowance, km/sec	0.200	0.200
Rendezvous Payload, lbs.*		
Titan 3D/Centaur/Burner II	1815	760
Titan 3F/Centaur/Burner II	2480	1060
Flight Time To Rendezvous, Years	4.16	3.12

* Retro Stage Propellant is Space-Storable at 400 sec I_{sp}

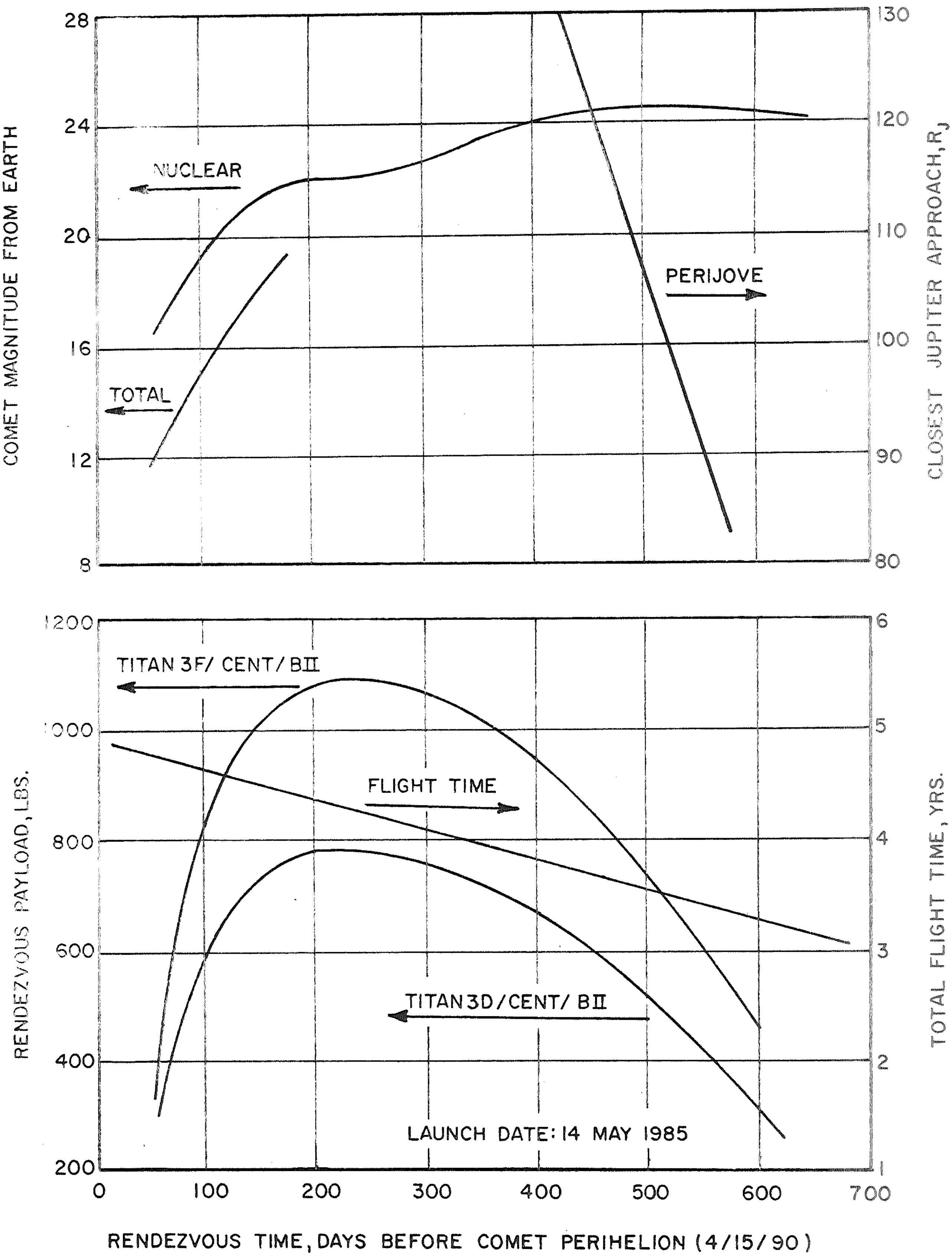

FIGURE 9. JUPITER-ASSISTED COMET TUTTLE-GIACOBINI-KRESAK/90
RENDEZVOUS MISSION PARAMETERS

characteristic precludes the opportunity to rendezvous 1000 pounds with the comet at 100 days before perihelion. An earlier date of 150 days before perihelion provides about 1015 pounds of spacecraft weight with the Titan 3F/Centaur/Burner II launch vehicle.

The mission parameters for rendezvous with T-G-K/90 at 150 days before perihelion are presented in Table 8. The earlier arrival date, probably necessary for adequate payload, further degrades already poor recovery characteristics for this apparition. The nuclear magnitude of T-G-K at this time is 21.4, too faint for earth-based detection. Hence an on-board optical tracker would be essential to the rendezvous maneuver of this mission. Miss distance at Jupiter is very large, in excess of 150 planet radii. The flight time of 4.52 years is nominal for ballistic comet rendezvous missions. T-G-K/90 does have a good opportunity for earth-based observations. The comet's predicted brightness is less than 12th magnitude (total) from 50 days before perihelion to 50 days after (see Table 1, Section 2). A polar plot of the rendezvous trajectory defined in Table 8 is shown in Figure 10.

3.2.4 Halley/86 Opportunity

A typical set of ballistic trajectory characteristics for fly-by opportunities to Halley's Comet are:

Flight time:	170 days
Arrival:	60 dbp
Launch velocity, V_c:	38,500 ft/sec
Approach velocity:	55.5 km/sec .

TABLE 8

COMET TUTTLE-GIACOBINI-KRESAK/90

JUPITER-ASSISTED RENDEZVOUS MISSION EXAMPLE

Launch Date	14 May 1985
Characteristic Velocity, ft/sec	49590
Injected Weight, lbs.	
Titan 3D/Centaur/Burner II	2040
Titan 3F/Centaur/Burner II	2760
Swingby Date	3 Jan. 1988
Hyperbolic Jupiter Approach Velocity, km/sec	6.09
Radius of Closest Approach, Jupiter Radii	> 140
Arrival Date	19 Nov. 1989
Arrival, Days Before Perihelion	146.6
Comet Brightness	
Nuclear Magnitude	21.4
Total Magnitude	18.1
Distance From Earth, AU	1.57
Distance From Sun, AU	2.04
Intercept Velocity, km/sec	2.626
Guidance ΔV Allowance, km/sec	0.200
Rendezvous Payload, lbs.*	
Titan 3D/Centaur/Burner II	735
Titan 3F/Centaur/Burner II	1015
Flight Time To Rendezvous, Years	4.52

* Retro Stage Propellant Is Space-Storable at 400 sec I_{sp}

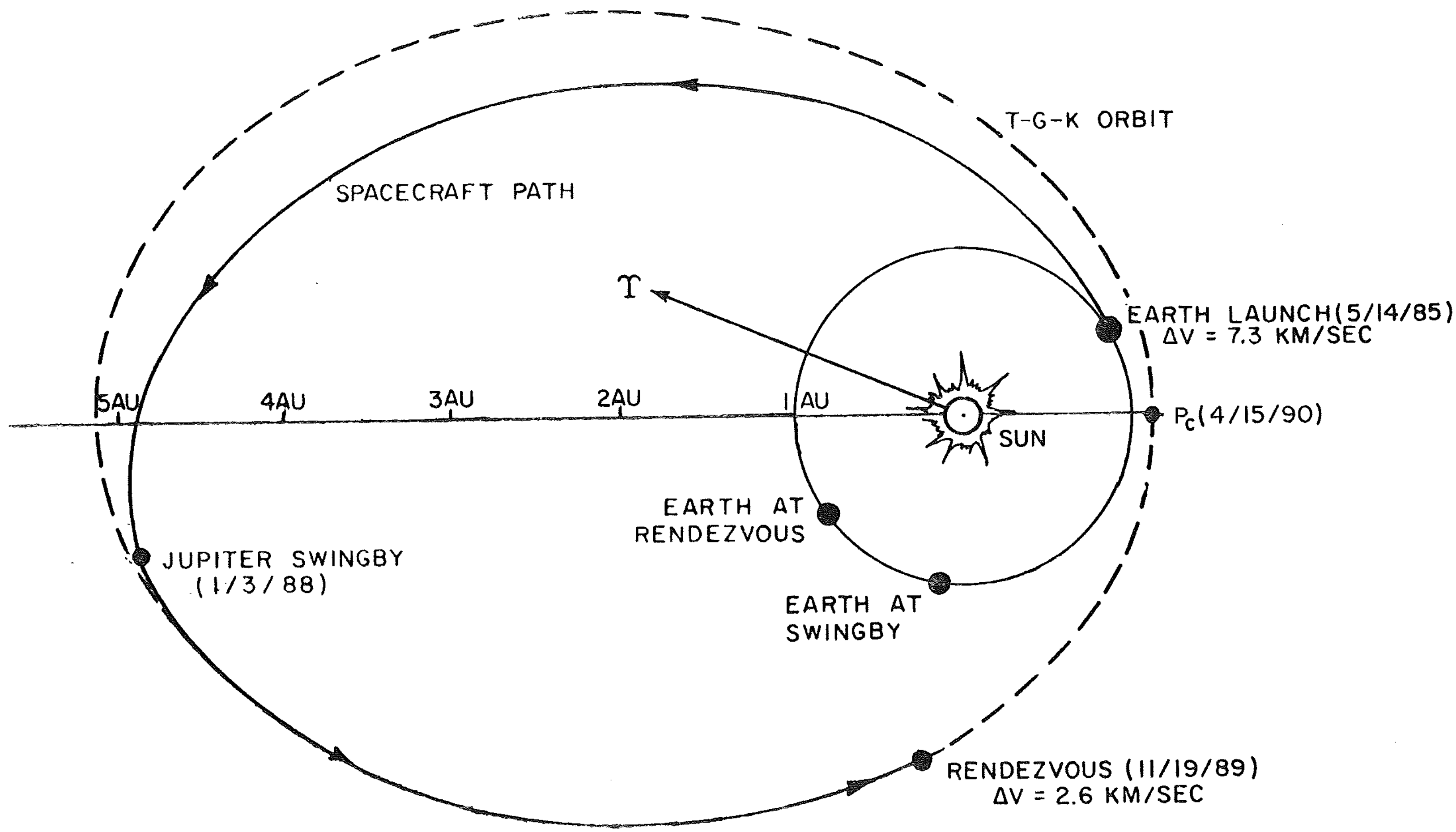

FIGURE 10. 4.5-YEAR JUPITER GRAVITY-ASSISTED MISSION TO TUTTLE-GIACOBINI-KRESAK/90

From a practical mission standpoint, the advantages of the relatively short flight time and low launch velocity are very much offset by the extremely high approach velocity. The flyby mode cannot be directly translated into a rendezvous mode since a retro maneuver of 55 km/sec is clearly not feasible. Hence, rendezvous can be accomplished only by changing the basic trajectory design. The penalty one must pay for this is both a longer flight time and a higher launch velocity.

The great difficulty in achieving a rendezvous with Halley is that the comet has retrograde motion with respect to the sun and that it is moving very fast near perihelion. A spacecraft launched from earth must, at some point, have the sense of its angular momentum reversed. Angular momentum changes are most efficiently made at large distances from the sun where the spacecraft velocity is small. Therefore, one possible rendezvous mode is a so-called aphelion pulse mission. An example worked out by Michielsen projects the aphelion distance to 7 au requiring a total flight time of nearly eight years. The reversal ΔV required at aphelion is 9.3 km/sec, and an additional ΔV increment is needed at the rendezvous point. The total ΔV requirement including launch would be about 30 km/sec.

A second ballistic rendezvous mode which allows a significant reduction in total ΔV is obtained by replacing the aphelion pulse requirement with a gravity-assist at either Jupiter or Saturn (Michielsen, 1968). Table 9 summarizes the trajectory and payload characteristics of Saturn-assist missions launched in 1973 and 1974 and Jupiter-assist missions launched in 1977 or 1978. Although the Saturn-assist results in both a lower launch velocity and arrival velocity impulse, the requirement of such an early launch and long flight time (11 - 12 years) probably precludes it from further consideration. Of the two Jupiter-assist missions opportunities, the 1977 launch has the advantage

TABLE 9

COMET HALLEY/86

GRAVITY-ASSISTED RENDEZVOUS MISSION EXAMPLES

Launch Date	30 APR 73	14 SEP 74	13 SEP 77	16 OCT 78
Charac. Velocity, km/sec	57500	58600	54400	54700
Injected Weight, lbs.				
Int-20/Centaur	4200	3400	6700	6500
Int-20/Centaur (F)/Kick	8700	7800	11800	11500
Saturn V/Centaur	12800	11300	18100	17700
Gravity-Assist Maneuver				
Swingby Body	Saturn	Saturn	Jupiter	Jupiter
Swingby Date	19 JAN 76	16 JAN 77	16 SEP 78	14 OCT 79
Swingby Radius, R(Body)	5.44	4.08	7.87	4.96
Arrival Date	18 APR 85	21 JUN 85	27 MAY 85	10 SEP 85
Time of Arrival, DBP	293	229	254	148
Comet Brightness				
Nuclear Magnitude	18.0	17.3	17.6	14.9
Total Magnitude	16.6	15.5	16.1	12.5
Distance From Earth, au	4.55	4.51	4.64	2.95
Distance From Sun, au	4.20	3.52	3.79	2.56
Intercept Velocity, km/sec	4.43	4.93	5.83	6.42
Midcourse ΔV, km/sec	0.60	0.60	0.60	0.60
Rendezvous Payload, lbs.*				
Int-20/Centaur	1230	965	390	235
Int-20/Centaur (F)/Kick	2210	1785	915	625
Saturn V/Centaur	3555	2885	1430	965
Flight Time, Years	11.7	10.8	7.7	6.9

* Two-Stage Retro Propellant Is Space-Storable With I_{sp} = 400 Sec

of lower energy requirements and, hence, larger payload capability. The transfer geometry for this opportunity is illustrated in Figure 11. Note that the relatively early arrival date means poorer earth-based recovery and tracking conditions for orbit determination prior to rendezvous. However, additional trajectory data suggests that the arrival date can be varied over several months without incurring an impulse penalty of greater than 100 m/sec.

The payload calculations assume that the sum of the guidance and arrival impulses are split equally between two propulsion stages, each operating with space-storable propellants (I_{sp} = 400 sec). Realistic inert mass fractions are taken into account. The rendezvous payload represents the total spacecraft weight delivered to the Halley orbit of which about 10-20 percent is available for experimental science. Assuming that the rendezvous payload should be on the order of 1000 pounds, it is seen that the Saturn V/Centaur launch vehicle would be required to accomplish the Jupiter-assisted Halley mission. The very high energy SIC/SIVB/Centaur (F)/Kick (15K) vehicle might be an alternative with 915 pounds payload capability if the Saturn V is unavailable.

A third variation of the ballistic flight mode, utilizing a powered maneuver at the Jupiter swingby, was investigated in an attempt to reduce the launch vehicle requirement (Kruse, 1968). The results showed that although the launch velocity and arrival velocity impulse were both reduced, the necessary powered maneuver of 6.29 km/sec at Jupiter caused the total propulsive requirement to increase. Hence, the basic unpowered gravity-assist at Jupiter remains the best mode for achieving a Halley rendezvous with adequate ballistic spacecraft.

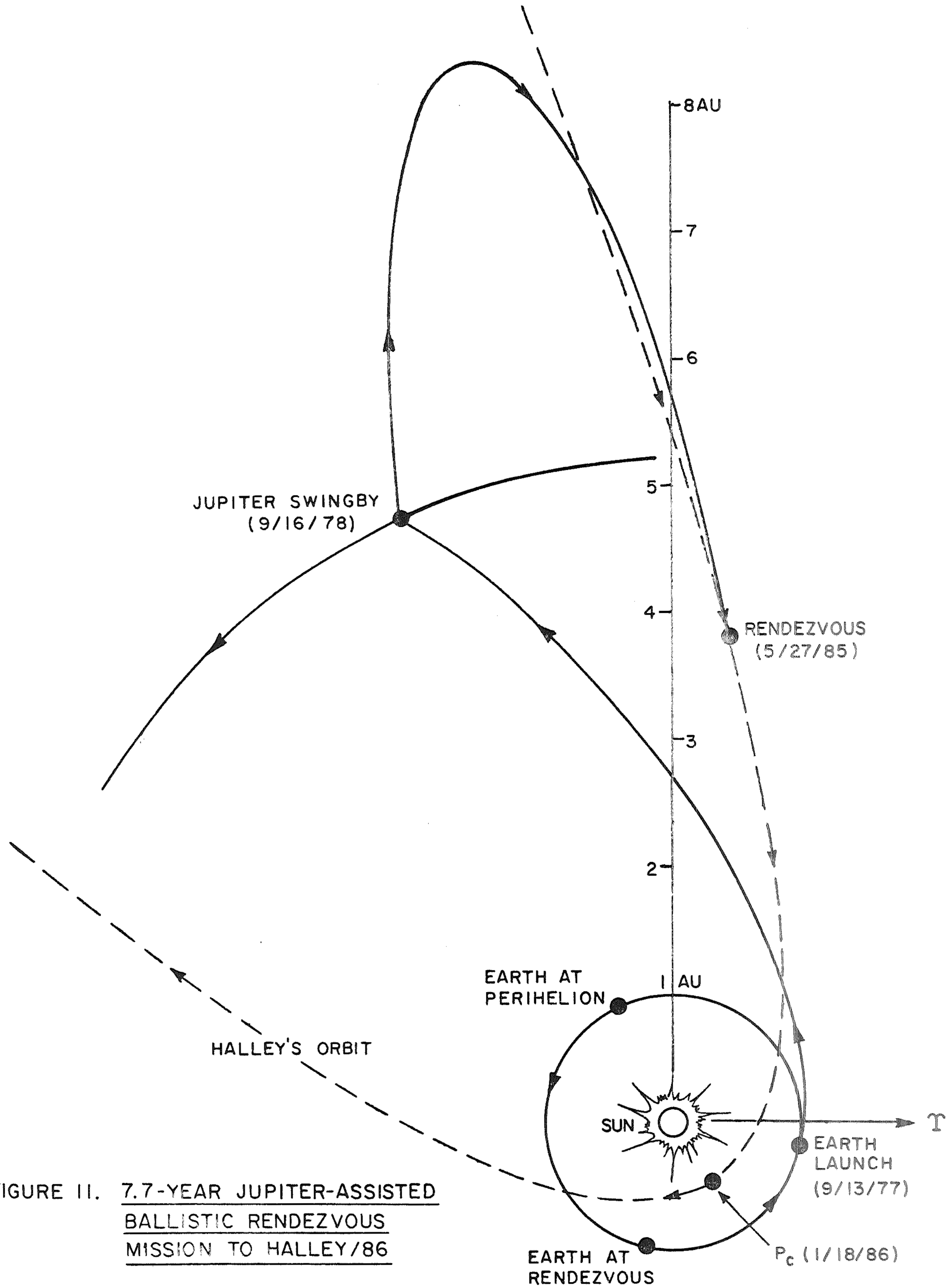

FIGURE 11. 7.7-YEAR JUPITER-ASSISTED BALLISTIC RENDEZVOUS MISSION TO HALLEY/86

3.2.5 Summary of Practical Gravity-Assisted Missions

Investigation of the gravity-assisted ballistic flight mode, as applied to comet rendezvous missions, was undertaken with the purpose of extending the number of useful or feasible missions and improving the payload/flight time results over those which were obtained for the impulsive unassisted mode and reported in Section 3.1. With the exception of the Halley/86 case, this effort has not been particularly successful. If the marginal cases of Honda-Mrkos-Pajduskova/85, which cannot be successfully observed from the earth, and Tuttle-Giacobini-Kresak/90, which is difficult to observe prior to rendezvous for guidance purposes, are disregarded, only the d'Arrest/82 case remains.

The improvement of the gravity-assisted mode over the unassisted impulsive mode for the d'Arrest/82 rendezvous mission consists of payload increases on the order of 100 to 200 pounds and flight time savings of about 1 to 2 months. A choice between these two modes would probably depend upon factors which were not considered in this study such as launch window and guidance problems and the possible use of the Jupiter swingby for an additional mission purpose.

The Halley/86 swingby analysis consisted of verifying existing results and updating payload computations with new estimates of propulsion parameters. Ballistic missions to Halley/86 are feasible but will involve extremely long flight times of from 7 to 8 years.

To summarize the ballistic flight mode results, five mission opportunities have been identified with acceptable payload (1000 pounds) and flight time (< 5 years) characteristics with the Titan 3D/Centaur/Burner II launch vehicle. These are d'Arrest/82, Kopff/83, Temple-2/88, Forbes/93 and Kopff/96. Several other comets, most notably Encke are also interesting rendezvous mission candidates if the larger Titan 3F/Centaur becomes available. Substantial improvements in the payload/flight time characteristics of the Jupiter-assisted comet rendezvous opportunities studied did not materialize. The use of low-thrust propulsion is considered in the following sections as an alternate propulsion system for increasing payload and/or decreasing flight time.

3.3 Nuclear-Electric Low-Thrust Mode

The application of electric propulsion to deep space missions may be viewed as providing a high performance upper stage capability as an alternative to chemical propulsion systems. In operation, the trajectory velocity requirements are attained at very low thrust acceleration (10^{-4} to 10^{-3} m/sec^2) over a significant fraction of the total flight time, but with a high propellant specific impulse (3,000 to 10,000 seconds). This results in a smaller propellant mass fraction to achieve a given total velocity impulse as compared to chemical propulsion. The low-thrust spacecraft has the inherent advantages of flight path flexibility and control of terminal conditions. Hence, it is particularly well suited for rendezvous with comets of high eccentricity and inclination.

The availability of reliable (long operational lifetime) and sufficiently lightweight powerplants is the key to realizing the performance potential of electric propulsion. One area of technology development is nuclear-electric powerplants wherein a nuclear thermionic system is utilized to generate the power necessary to operate the ion thrusters. The nuclear-electric flight mode is characterized by constant power level throughout the flight independent of the spacecraft distance from the sun. Nuclear-electric propulsion may reach a flight readiness status by the early or mid-1980's. Hence, a possible application exists for future comet rendezvous missions, particularly the Halley/86 opportunity.

Nuclear-electric low-thrust trajectories for comet rendezvous missions were generated by a computer program based on a Newton-Raphson, finite-difference algorithm (Ragsac, 1967). Three-dimensional, elliptical orbits are assumed for both earth and the target comet of interest. In obtaining the trajectory data, the arrival date at the comet was fixed (typically, several month's before perihelion) and the launch date was varied to represent a range of flight times. The propulsion system is assumed to operate at constant thrust and constant jet velocity (specific impulse), but a coast period is allowed if required by the optimization conditions. Low-thrust propulsion is initiated outside of the earth's sphere of influence after a high thrust launch and injection to a selected hyperbolic excess velocity (VHL). VHL is a parameter of the payload optimization and may be considered freely selectable.

Each trajectory between a given launch and arrival date is optimum in the sense of minimum propellant expenditure or, equivalently, minimum value of the trajectory energy parameter

$$J = \int_{o}^{t_f} a^2 (t) \, dt \quad , \quad m^2/sec^3 \qquad (3)$$

where t_f is the heliocentric flight time and $a(t)$ is the thrust acceleration magnitude. Thrust direction is not constrained, but rather is allowed to take on its optimum value at all points along the trajectory. The acceleration time history may be related to the propulsion system parameters: thrust (F), electric power rating (P_e), power conversion efficiency (η), specific impulse (I_{sp}) or jet velocity (c), initial spacecraft mass (m_o), and propellant mass flow rate ($\dot{m}_p$):

$$a(t) = \frac{F}{m_o - \int_o^t \dot{m}_p \, dt} \quad , \text{ m/sec}^2 \tag{4}$$

$$\dot{m}_p = \frac{F}{c} = \frac{F}{g_o I_{sp}} \quad , \quad \text{kg/sec} \tag{5}$$

$$P_e = \frac{Fc}{2\eta} \quad , \quad \text{watts.} \tag{6}$$

The constant g_o is equal to earth's surface gravity, 9.8066 m/sec^2. It is understood that $a = F = \dot{m}_p = 0$ during a trajectory coast period. Power conversion efficiency is equal to the product of power conditioning efficiency (η_{PC}) and thruster efficiency (η_T)

$$\eta = \eta_{PC} \quad \eta_T \tag{7}$$

where η_T varies with the specific impulse design point. Figure 12 shows the thruster efficiency curve assumed in the present analysis. This efficiency projected to the post-1980 state-of-the-art is somewhat more optimistic than that obtained from present generation thrusters. The power conditioning efficiency is assumed to be 93 percent.

Initial spacecraft mass is a function of the launch vehicle selection and the launch hyperbolic velocity. The three launch vehicles considered are the Titan 3D/Centaur, Titan 3F/Centaur, and Intermediate-20 Saturn. The injected

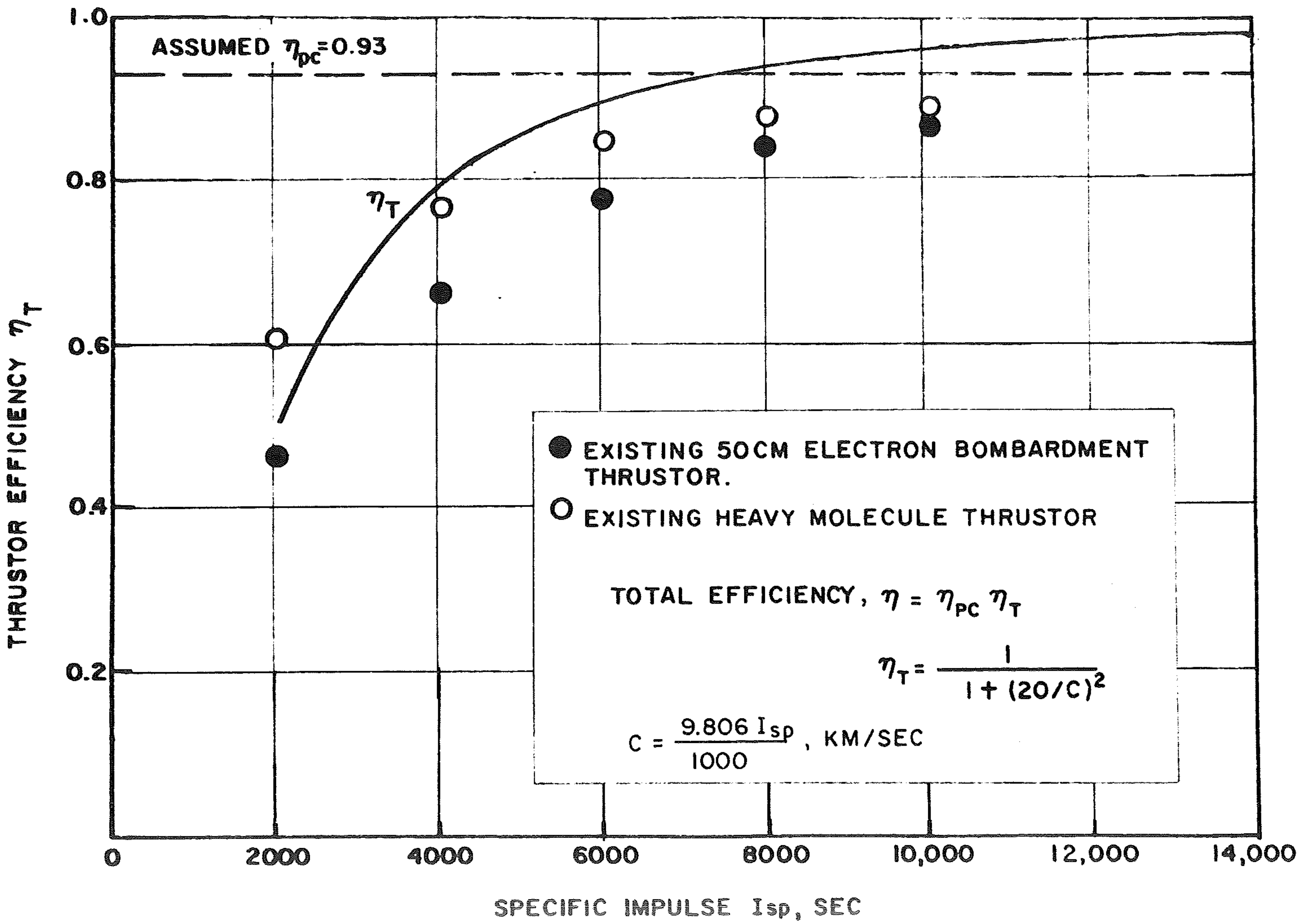

FIGURE 12. POWER CONVERSION EFFICIENCY ASSUMED IN ANALYSIS.

launch vehicle weight is assumed to be equivalent to the initial gross weight of the electric spacecraft.

The initial mass is defined as consisting of the sum of the following masses: propulsion system (m_{ps}), propellant (m_p), tankage (m_t) and net spacecraft mass or net payload (m_n).

$$m_o = m_{ps} + m_p + m_t + m_n \tag{8}$$

For nuclear-electric powerplants, m_{ps} would consist of the reactor, radiation shield, radiators, power conversion and conditioning equipment, electric thrustors, and integrating structure. Net payload, m_n, includes the science payload, communication and data processing equipment, and guidance and control equipment. The tankage mass is taken to be proportional to the propellant mass:

$$m_t = k_t \, m_p \tag{9}$$

and is typically estimated to be 3 to 10 percent of m_p (k_t = 0.06 is assumed in the subsequent payload analysis).

A convenient figure of merit of electric propulsion technology is the propulsion system specific mass α_{ps}:

$$\alpha_{ps} = \frac{m_{ps}}{P_e} \tag{10}$$

The actual variation of propulsion system mass with the power rating is as yet not precisely defined for future nuclear-electric systems, although there does exist good estimates of m_{ps} at discrete power design points. It is known that m_{ps} decreases as P_e decreases but probably approaches some fixed minimum value even as P_e goes to zero. For the purpose of this analysis, it will be assumed that mass is linearly related to power in the following way:

$$m_{ps} = k_1 + k_2 P_e \tag{11}$$

where k_1 and k_2 are constants.

Alternatively, then, the specific mass of the propulsion system varies inversely but asympotically with power:

$$\alpha_{ps} = \frac{k_1}{P_e} + k_2 \tag{12}$$

Figure 13 shows two curves of α_{ps} versus P_e which are assumed for the payload analysis. The constants k_1 and k_2 were determined from recently estimated specific mass data at power design points of 100 kw and 300 kw (Davis, 1969). The nominal or early technology estimates are based on current design concepts, materials and laboratory development of thermionic reactor systems. Advanced technology estimates projected to the post-1975 period offer weight reductions in all subsystems but principally in the areas of power conditioning, radiator and structure.

Performance analysis of electrically propelled spacecraft is somewhat complicated by the interdependence of numerous trajectory and propulsion system parameters as outlined above. However, a suitable link between these parameters is provided by the trajectory energy parameter J. The relationship between J and spacecraft mass is given by:

$$m_f = \frac{m_o}{1 + \dfrac{J\ m_o}{2\eta P_e}} \tag{13}$$

$$= m_o - m_p$$

where m_f is the final gross mass at $t = t_f$. Clearly, for given

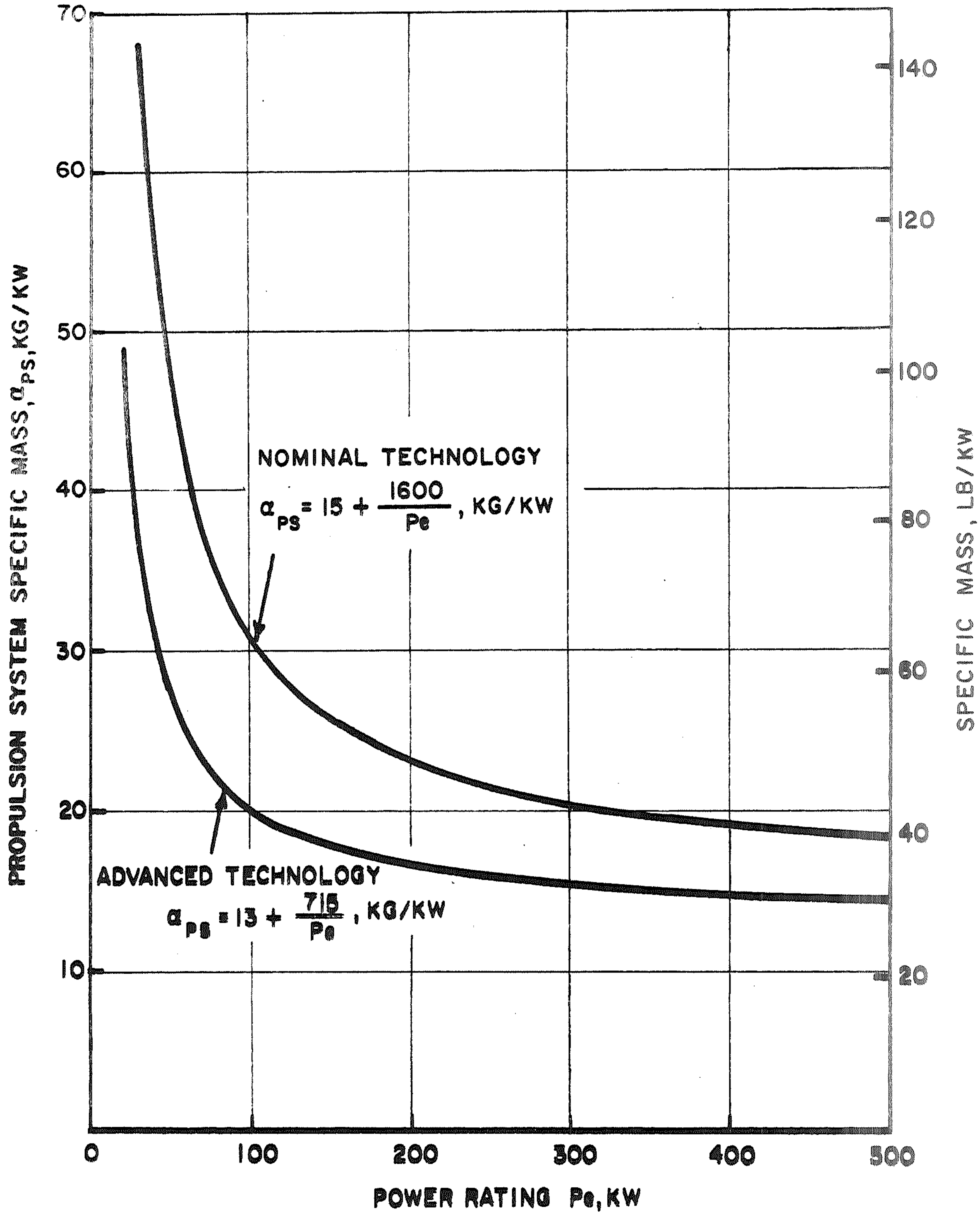

FIGURE 13. PROPULSION SYSTEM TECHNOLOGY CURVES ASSUMED FOR NUCLEAR-ELECTRIC SPACECRAFT

values of m_o, P_e and η, a minimum J trajectory yields a maximum value of m_f.

The value of J obtained for operation at constant thrust and specific impulse over a given trajectory depends upon the propulsion parameters P_e and I_{sp}, and on the launch hyperbolic velocity VHL. Assume for the moment a specified value of VHL. Then, for a given value of P_e, there is some optimal I_{sp} which results in a minimum J for that P_e. To a very good approximation this minimum J is invariant with P_e providing the corresponding optimum I_{sp} is chosen. Again, to a good approximation, a second invariant of the optimum trajectory is the so-called characteristic length L (Zola, 1964). As modified, (Mascy, 1969), the characteristic length of rendezvous trajectories is:

$$L = \frac{c^2}{a_o} \left[\left(1 - \sqrt{1 - \frac{a_o t_p}{c}} \right)^2 - \frac{0.4 a_o}{c} (t_f - t_p) \ \mathrm{lm} \left(1 - \frac{a_o t_p}{c}\right) \right] \tag{14}$$

where t_p is the total propulsion time ($t_p \leq t_f$) and a_o is the initial thrust acceleration. The implication of assuming that J and L are invariant along an optimal trajectory is that the time consuming process of trajectory optimization need not be repeated for different propulsion system parameters. In other words, for given values of VHL and t_f, the optimum trajectory parameters (J, L) are computed only once using any reasonable set of propulsion system parameters. The payload analysis may then be performed afterwards utilizing the algebraic expressions given above. Validity checks on this method of approximation show that the net payload m_n results are accurate to within a few percent. The subsequent payload analysis for the Halley rendezvous opportunity will show the effect of VHL and P_e on maximizing m_n.

3.3.1 Halley/86 Opportunity

The arrival date at Halley's Comet was selected to be November 24, 1985 which is 55 days before the perihelion passage. At this point the geocentric distance is near minimum and the comet brightness as seen from earth is about 4th magnitude. A range of launch dates in 1983-84 representing a flight time variation of 500 to 1000 days was investigated.

Figure 14 shows a representative minimum J versus flight time characteristic for a fixed value of launch hyperbolic velocity. The lower curve, shown for reference purposes, gives the variable thrust solution. This yields the ideal optimum performance but is impractical from a propulsion system standpoint since the thrust and specific impulse are required to vary over a wide range. The constant thrust solution shown by the upper curve has a typical penalty of about 15 percent. Generally, J was found to decrease with increasing flight time over the range of times considered. However, there are small anomalies in this general trend which may be attributed to the geometric configuration of the earth launch position and the Halley position at the fixed arrival date. The earth's period of 365 days appears to be correlated with these anomalies.

Figure 15 shows the effect of the launch hyperbolic velocity on the J requirements for several fixed flight time trajectories. Since a larger VHL means that more energy is allocated to the high-thrust escape phase of the mission, the low-thrust energy requirements decrease as shown. For the short flight of 540 days, J varies between 56 and 49 m^2/sec^3 as VHL varies between 0 and 5 km/sec. The corresponding range of J for the longer flight of 940 days is 21.4 to 17.2 m^2/sec^3. It is noted that the results for the 850-day trajectory appear quite

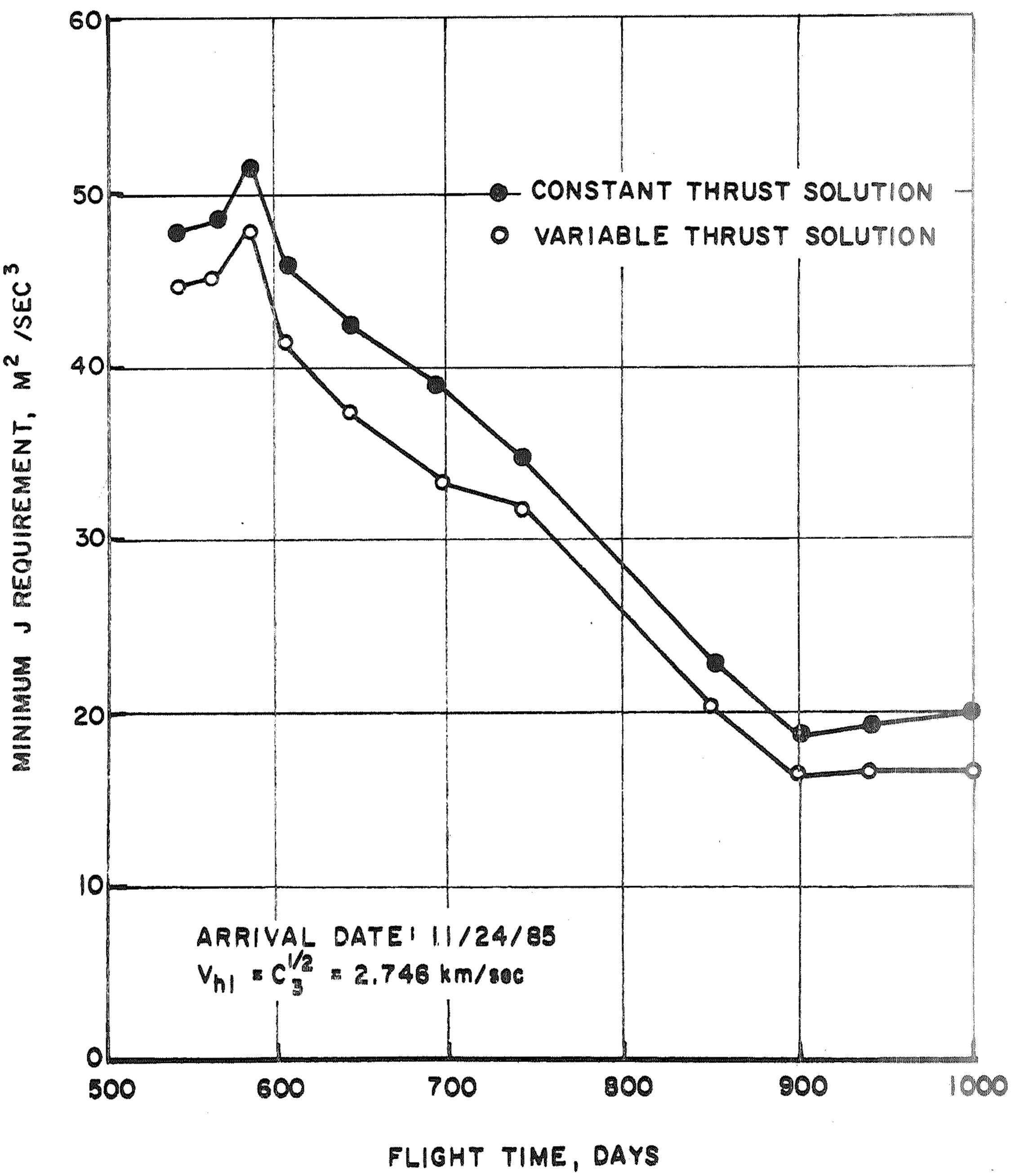

FIGURE 14. REPRESENTATIVE J REQUIREMENTS FOR LOW THRUST RENDEZVOUS WITH HALLEY'S COMET.

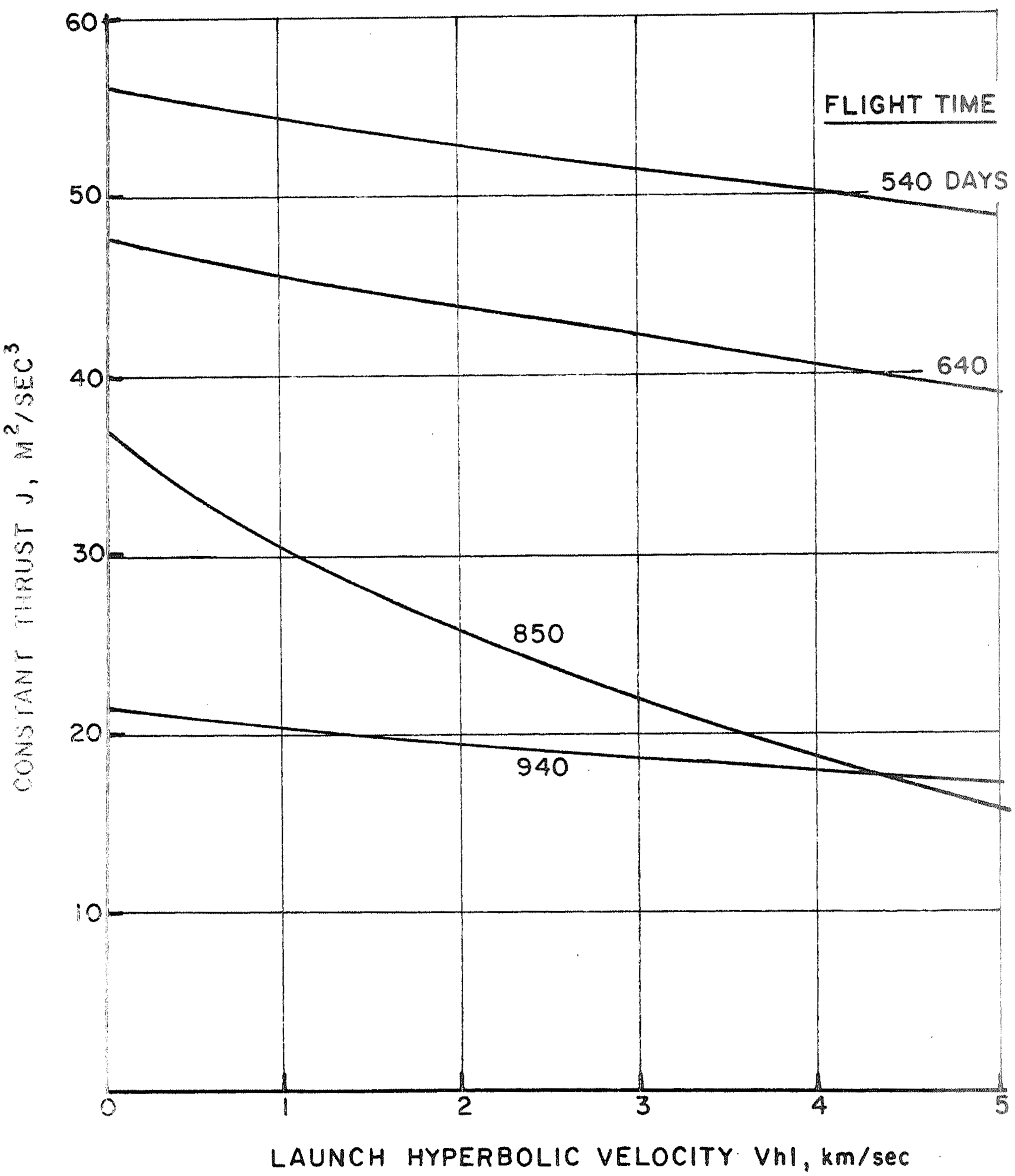

FIGURE 15. EFFECT OF LAUNCH HYPERBOLIC VELOCITY ON J REQUIREMENTS FOR HALLEY RENDEZVOUS, ARRIVAL 11/24/85.

different inasmuch as the variation of J with VHL is more than a factor of 2, and that the 850 day flight requires a smaller J than the 940 day flight when VHL > 4.3 km/sec. This unexpected behavior was checked and verified by another independent trajectory optimization program. An apparent explanation of this result may be offered with the help of Figure 16 which shows how the earth's longitudinal position at launch for various flight times is situated with respect to the arrival position at the comet. For the sake of definition, we will refer to trajectories whose initial motion is outward from the earth and whose total travel angle is less than 360° as <u>direct</u> trajectories. Those trajectories which initially go inward toward the sun and may (but not necessarily) travel more than one revolution are referred to as <u>indirect</u> trajectories. Of the six launch positions indicated, the 640, 690 and 740-day missions are indirect trajectories. A sketch of the 690 trajectory is shown. The 540, 850 and 940-day flights were computed as direct trajectories. Now, as to the explanation, it appears that there is a minimum J trajectory mode change which takes place at some flight time in the vicinity of 850 days. It is therefore hypothesized that there should exist (for lower values of VHL) an indirect 850 day flight having a smaller J requirement than the direct flight. Kruse describes an 855 day indirect flight to Halley (for VHL = 0) which tends to verify this hypothesis (Kruse, 1968). There is a need for a further definitive analysis of the two trajectory modes.

Figures 17 through 20 illustrate the low thrust trajectory shapes for flight times of 540, 640, 850 and 940 days. Thrust direction is indicated by the arrows at several points along the trajectory. It is noted that the thrust vector rotates slowly relative to an inertial coordinate frame. In all cases angular momentum reversal occurs at or near the aphelion distance of the trajectory which is about 2.5 au on the 540-day

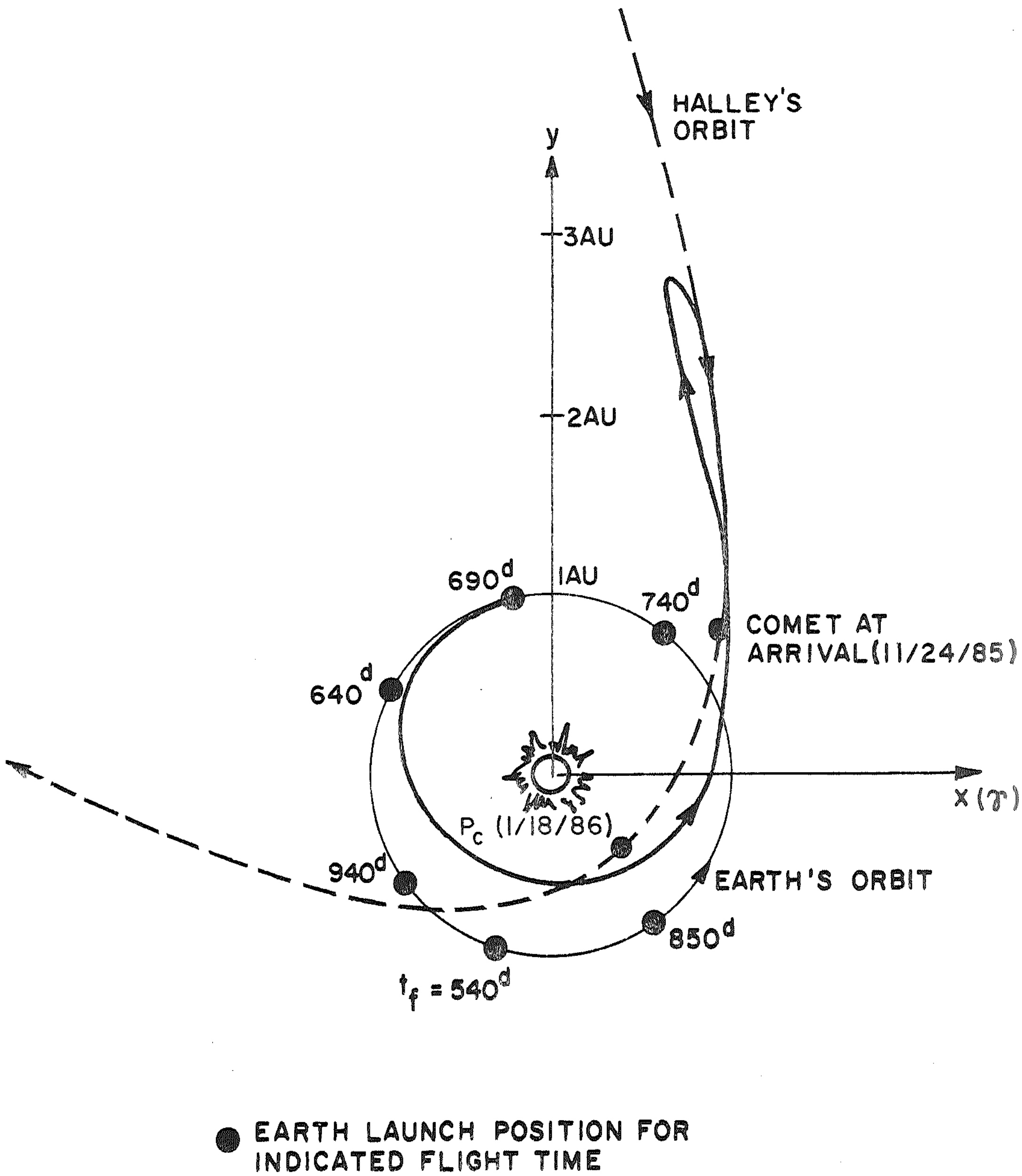

FIGURE 16. LAUNCH-ARRIVAL POSITION GEOMETRY FOR RENDEZVOUS TRAJECTORIES TO HALLEY'S COMET.

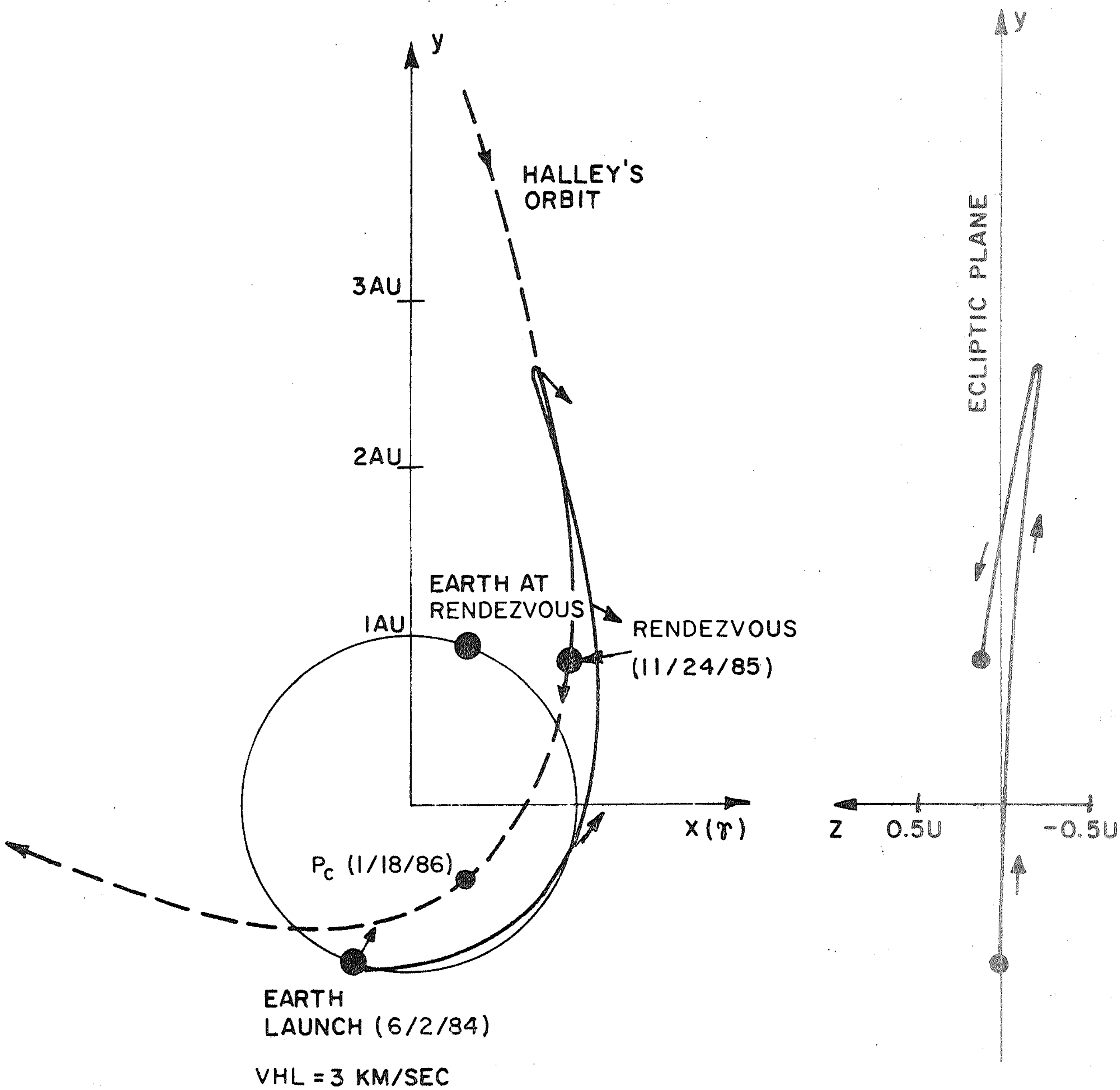

FIGURE 17. 540-DAY RENDEZVOUS TRAJECTORY TO HALLEY'S COMET, NUCLEAR-ELECTRIC LOW-THRUST FLIGHT MODE.

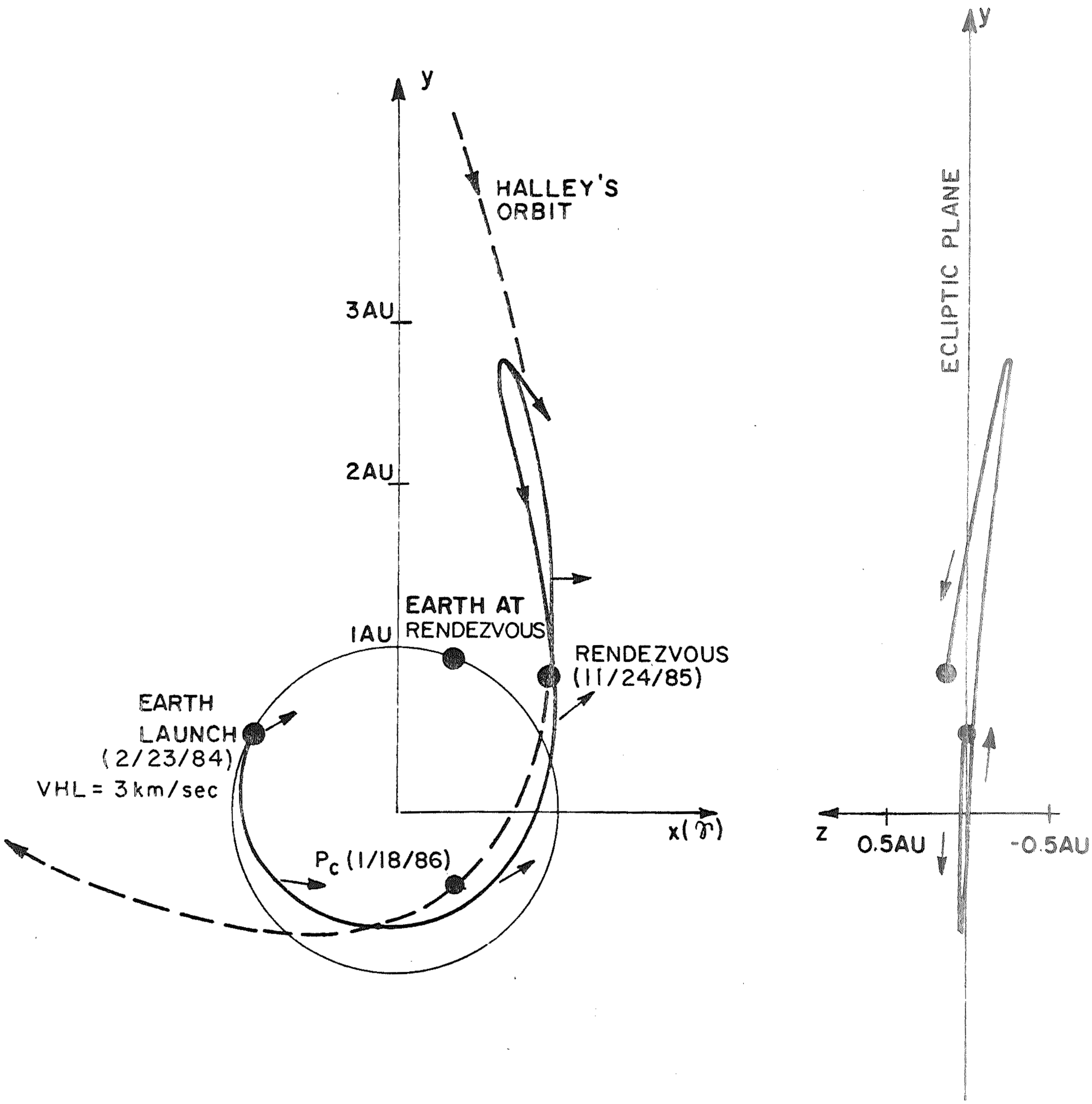

FIGURE 18. 640-DAY RENDEZVOUS TRAJECTORY TO HALLEY'S COMET, NUCLEAR-ELECTRIC LOW-THRUST FLIGHT MODE.

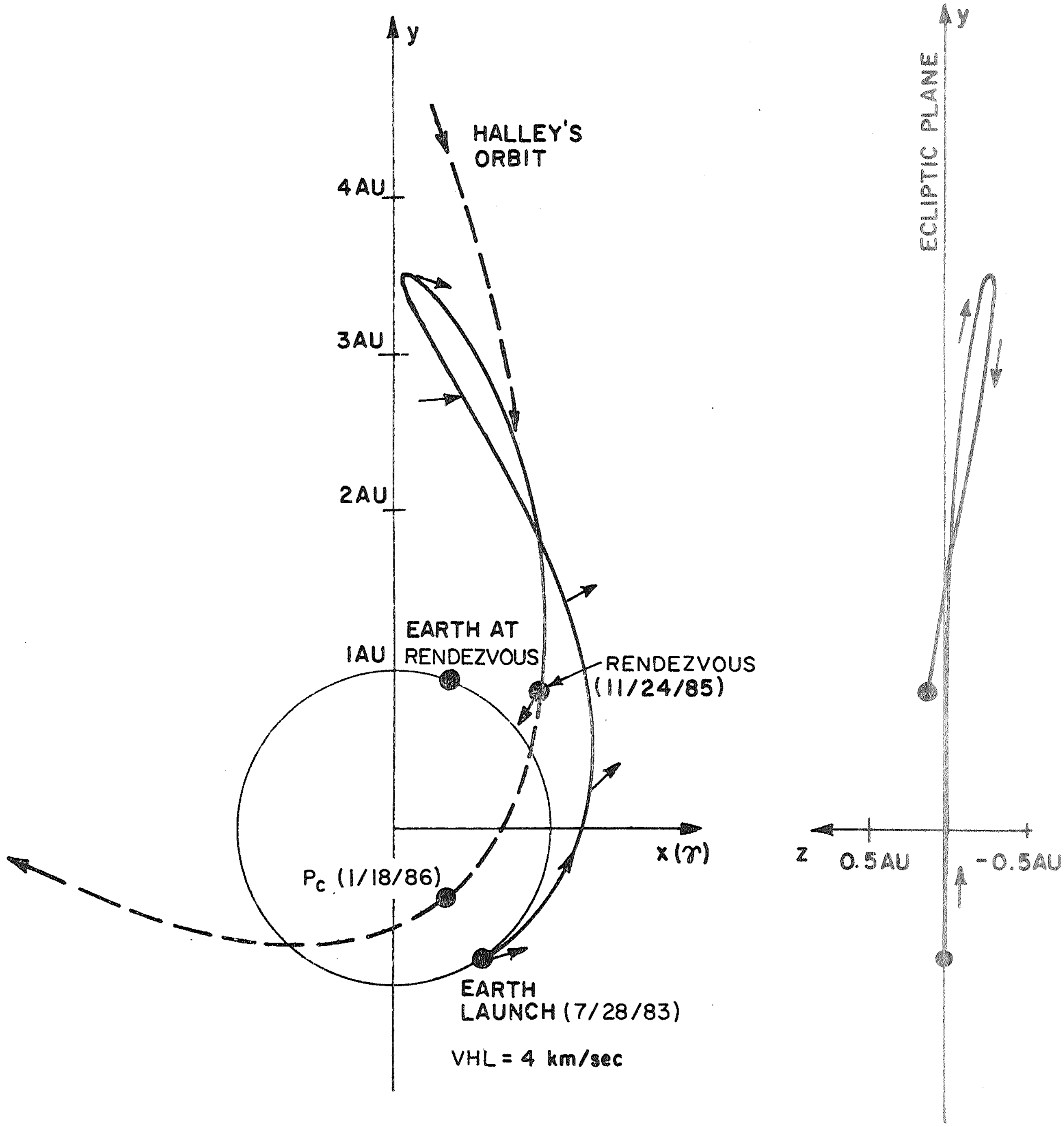

FIGURE 19. 850-DAY RENDEZVOUS TRAJECTORY TO HALLEY'S COMET, NUCLEAR-ELECTRIC LOW-THRUST FLIGHT MODE

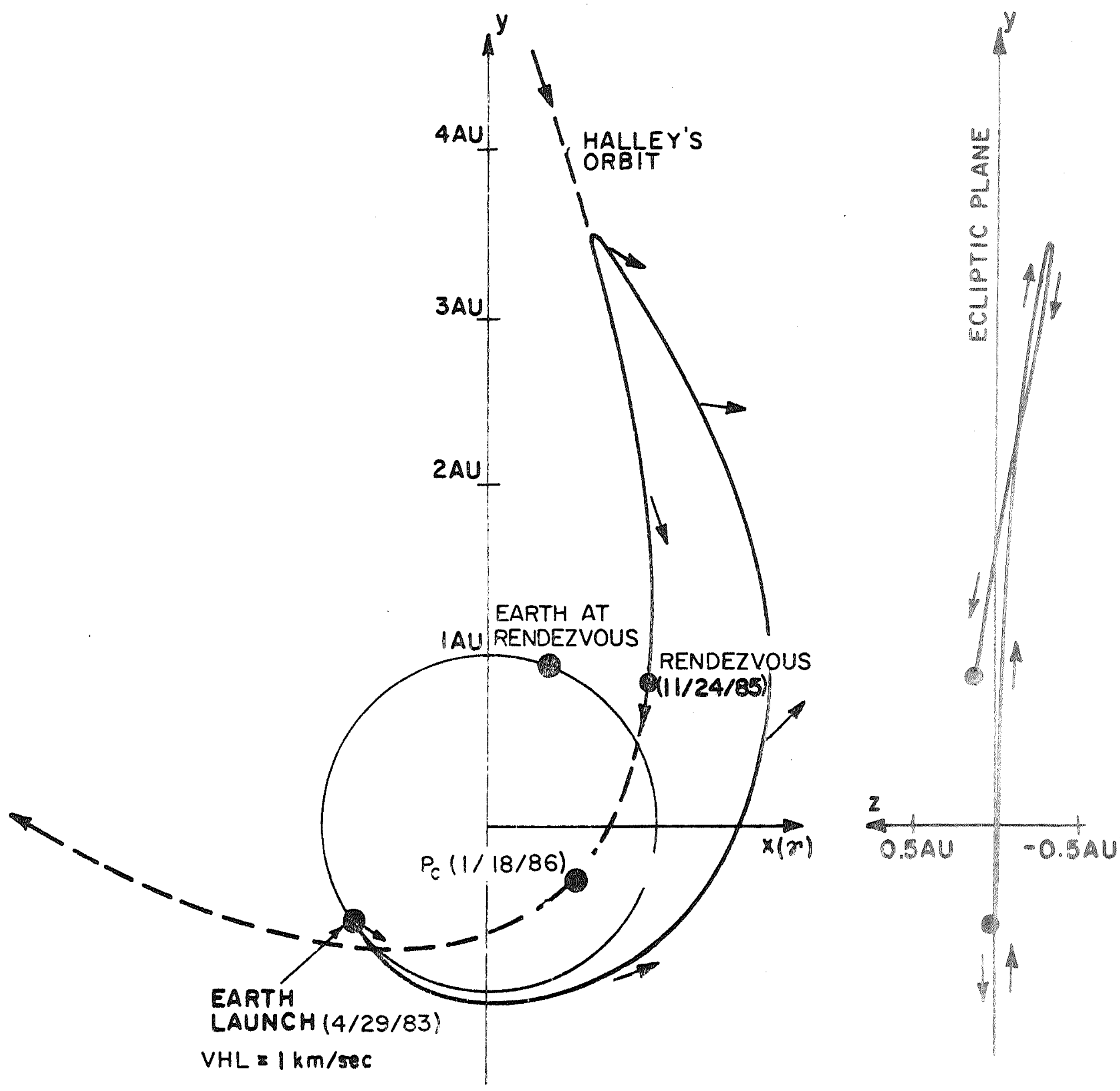

FIGURE 20. 940-DAY RENDEZVOUS TRAJECTORY TO HALLEY'S COMET, NUCLEAR-ELECTRIC LOW-THRUST FLIGHT MODE

flight and 3.5 au on the 940-day flight.

The effect of power rating and launch hyperbolic velocity on the net payload optimization is illustrated in Figure 21 for the 940-day flight utilizing the Titan 3F/Centaur launch vehicle and the advanced electric propulsion technology. Optimum performance occurs at about VHL = 1 km/sec and P_e = 160 kw yielding a maximum net payload of 4300 pounds. The largest payload available at some off-optimum power rating is given by the upper envelope of the VHL curves. For example, at P_e = 100 kw the optimum VHL and m_n are 2 km/sec and 3800 pounds, respectively. At P_e = 40 kw, the maximum payload available falls off to about 1400 pounds at VHL = 5 km/sec. One of the advantages of employing a reduced power rating may be the lower cost associated with developing the powerplant. Another is the multi-mission applications of an electric propulsion spacecraft utilizing a fixed design powerplant. Hence, power rating and payload could become important tradeoff parameters in future mission studies.

Figures 22a, b and c show the maximum payload capability as a function of power rating for each of the launch vehicles considered, the two assumed levels of propulsion system technology, and flight times of 540, 640, 850 and 940 days. These results assume approximately optimum values of VHL and I_{sp} for each power rating. Typically, the range of optimum VHL is 0-6 km/sec where the higher velocities are associated with low power rating. The range of optimum I_{sp} is 4000 - 14,000 seconds where the lower values of I_{sp} are associated with low power rating. At the optimum power points the range of I_{sp} is much narrower, 5000 - 9000 seconds. It is noted that the Titan-class launch vehicles provide marginal or vanishing payload for the shorter flights to Halley's Comet. On the other hand, the Intermediate-20 Saturn launch vehicle would not be required at longer flight times since delivered payload becomes excessive for a rendezvous mission. Another point to be noted is the very significant

LAUNCH VEHICLE : TITAN 3F/CENTAUR

TECHNOLOGY LEVEL : ADVANCED ($\alpha = 13 + \frac{715}{P_e}$ kg/kwe)

POWER EFFICIENCY : $\eta = \frac{0.93}{1 + (20/C)^2}$; C IN km/sec

TANKAGE FACTOR : $K_t = 0.06$

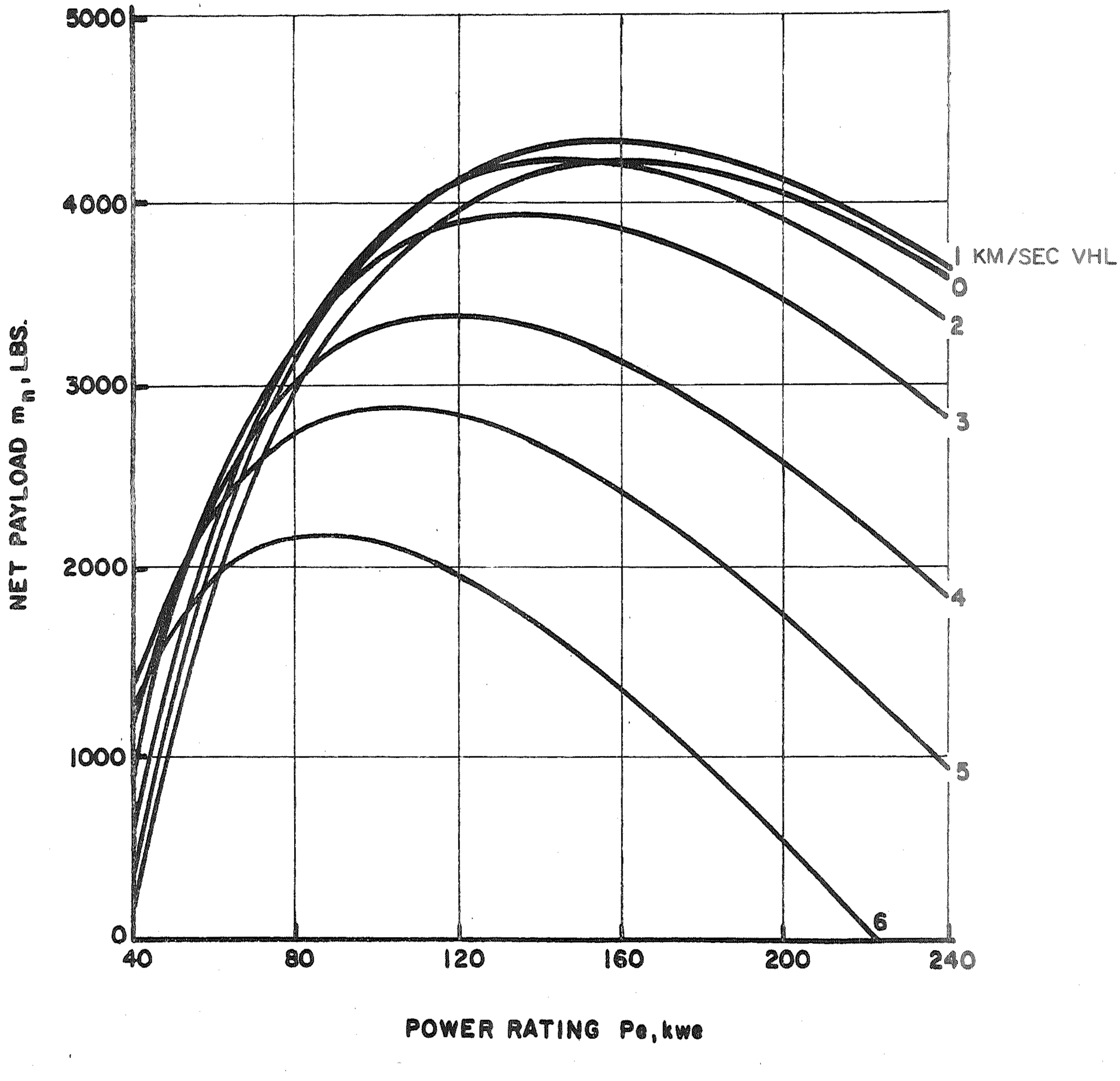

FIGURE 21. PAYLOAD OPTIMIZATION FOR 940 DAY RENDEZVOUS TRAJECTORY TO HALLEY'S COMET WITH NUCLEAR-ELECTRIC SPACECRAFT, ARRIVAL 11/24/85

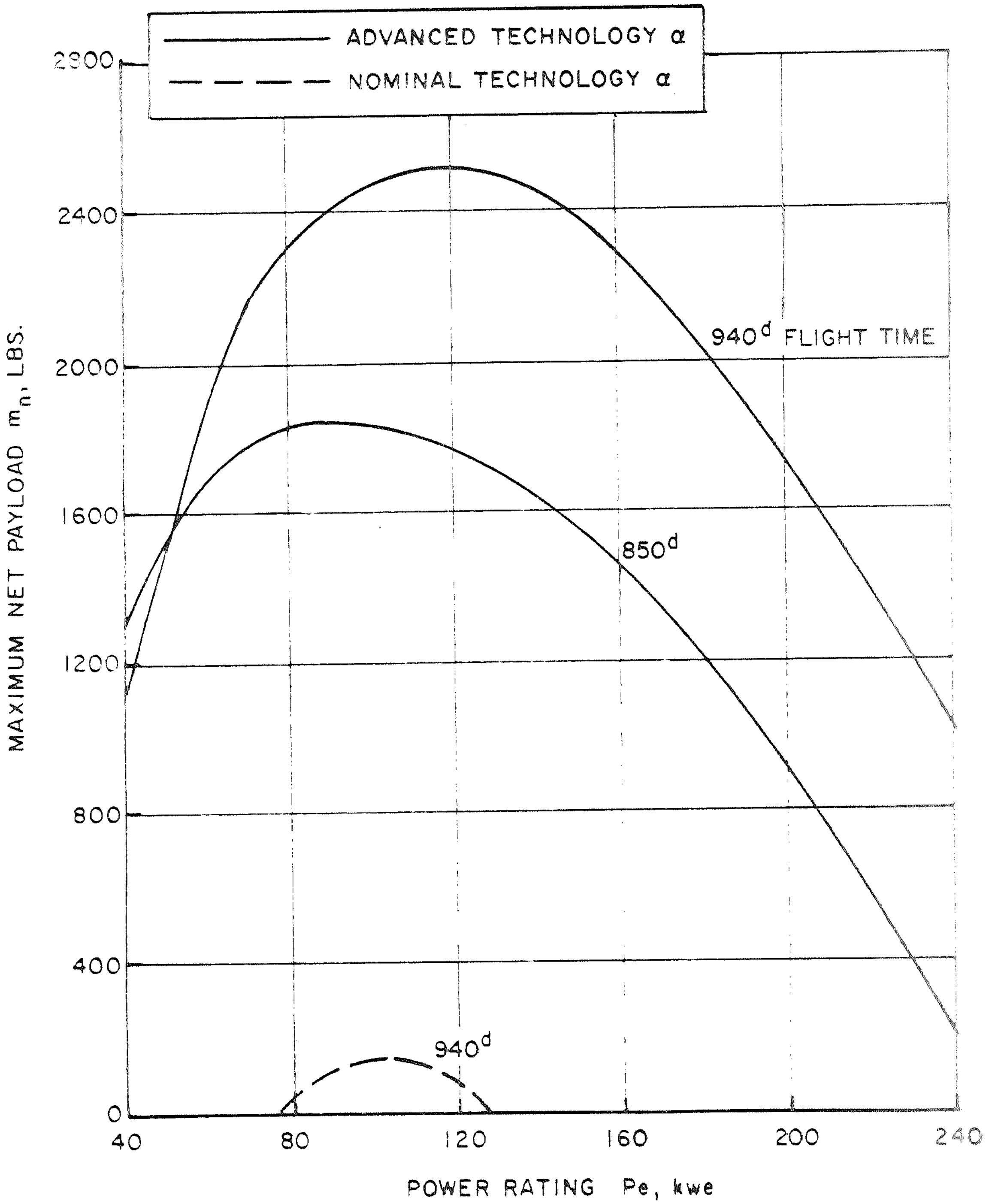

FIGURE 22a. PAYLOAD CAPABILITY OF NUCLEAR-ELECTRIC SPACECRAFT FOR RENDEZVOUS MISSION TO HALLEY'S COMET, ARRIVAL 11/24/85, TITAN 3D/CENTAUR LAUNCH VEHICLE

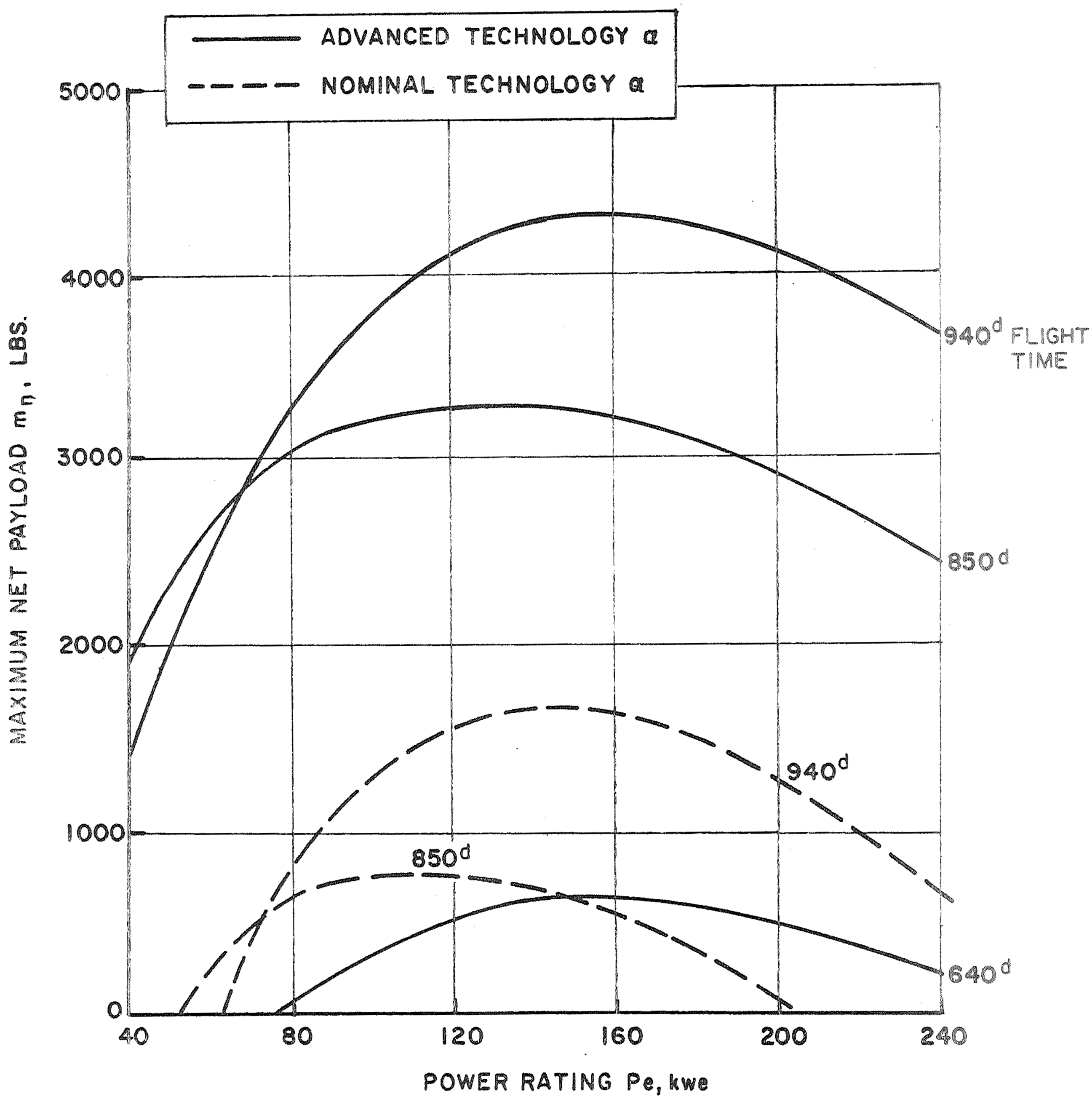

FIGURE 22b. PAYLOAD CAPABILITY OF NUCLEAR-ELECTRIC SPACE-CRAFT FOR RENDEZVOUS MISSION TO HALLEY'S COMET, ARRIVAL 11/24/85, TITAN 3F/CENTAUR LAUNCH VEHICLE

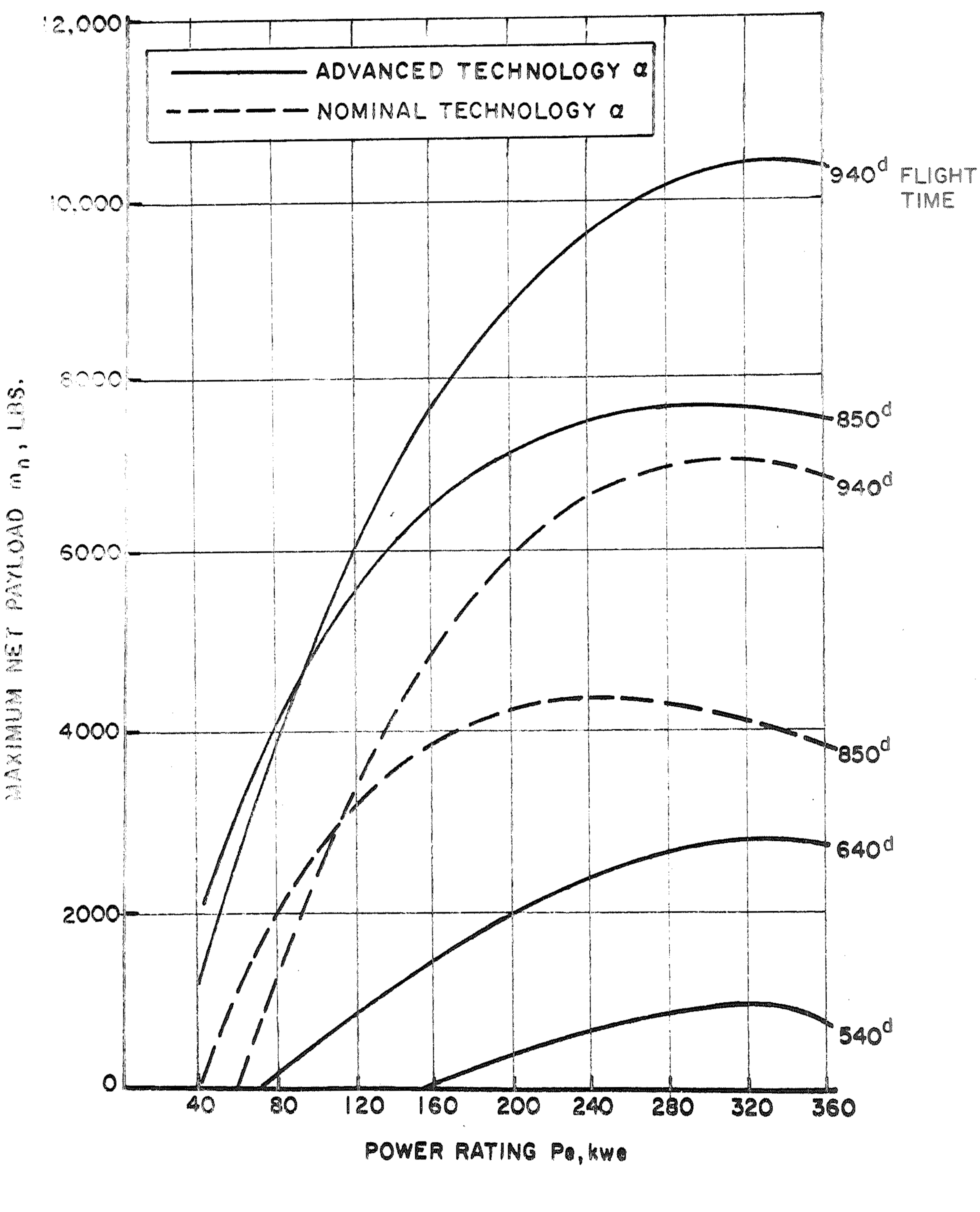

FIGURE 22c. **PAYLOAD CAPABILITY OF NUCLEAR-ELECTRIC SPACECRAFT FOR RENDEZVOUS MISSION TO HALLEY'S COMET, ARRIVAL 11/24/85**, SIC/SIVB LAUNCH VEHICLE

effect of the propulsion system specific mass. For example, the Titan 3F/Centaur employed for the 940-day flight yields a maximum payload of 4300 pounds if the advanced technology is assumed. The payload is reduced to 1650 pounds if the nominal technology is assumed.

Table 10 summarizes the payload capability of the nuclear-electric flight mode for Halley rendezvous assuming that all propulsion system parameters are optimized. A tentative but conservative mission selection would assume the nominal propulsion system technology, the Titan 3F/Centaur launch vehicle and the 940-day flight time. The electric spacecraft would be launched to a slightly hyperbolic escape trajectory, and operate at a specific impulse of about 7200 seconds and a power rating of 140 kw (α_{ps} = 58 lbs/kwe). The net spacecraft weight at comet rendezvous would be 1650 pounds of which 200-300 pounds should be available for the science experiments. Utilization of the large power source is, of course, an added bonus. To take advantage of this performance potential for the very exciting Halley mission opportunity, the nuclear-electric spacecraft would have to be developed and made operational by the early 1980's.

3.3.2 Encke/90 Opportunity

A limited trajectory analysis of the 1990 Comet Encke rendezvous opportunity has been performed in order to compare nuclear-electric propulsion with the other propulsion modes for a short-period comet. Several flight times between 400 and 600 days were investigated. The J requirements of the 500 and 600-day flights were nearly the same -- about 18.8 m^2/sec^3 and 16.4 m^2/sec^2, respectively, for VHL = 2 km/sec. A very high J requirement of 61 m^2/sec^3 was found for the 400-day flight. Payload capabilities for a 500-day flight are presented (Figure 23)

TABLE 10

POWER AND PAYLOAD SUMMARY

FOR

NUCLEAR-ELECTRIC LOW-THRUST HALLEY RENDEZVOUS MISSIONS *

LAUNCH VEHICLE	MISSION FLIGHT TIME (DAYS)							
	540		640		850		940	
	POWER (KWE)	PAYLOAD (LBS)	POWER (KWE)	PAYLOAD (LBS)	POWER (KWE)	PAYLOAD (LBS)	POWER (KWE)	PAYLOAD (LBS)
NOMINAL PROPULSION-SYSTEM TECHNOLOGY:								
TITAN 3D/CENTAUR +	—	—	—	—	—	—	100	150
TITAN 3F/CENTAUR	—	—	—	—	100	750	140	1650
INT-20 SATURN	—	—	—	—	200	4350	300	7100
ADVANCED PROPULSION-SYSTEM TECHNOLOGY:								
TITAN 3D/CENTAUR	—	—	—	—	80	1850	120	2500
TITAN 3F/CENTAUR	—	—	140	650	140	3300	160	4300
INT-20 SATURN	320	950	340	2850	300	7650	340	10,400

* ARRIVAL DATE FIXED AT 55 DBP

\+ LONGER FLIGHT TIMES OF 1050 DAYS AND 1300 DAYS WERE COMPUTED FOR THIS CASE WITH RESULTANT PAYLOADS OF 600 LBS. AND 1800 LBS. RESPECTIVELY.

as a function of power rating for nominal and advanced powerplant technology and Titan-class launch vehicles. A 1000-pound payload at Encke rendezvous is well within the capability of a Titan 3F/Centaur and a nuclear-electric low-thrust stage developed with nominal technology. A trajectory profile of the 500 day mission is illustrated in Figure 24. The flight path extends to about 2.6 a.u. from the sun and rendezvous occurs 100 days before Encke's perihelion passage (11/8/90). Since Encke's orbital period is about 3.3 years, the configuration shown in Figure 24 is essentially similar to the 1980 launch opportunity (3 Encke periods earlier).

3.3.3 Summary of Nuclear-Electric Missions

Using a prediction of nuclear power supply technology, nuclear-electric rendezvous with Halley/86 has been studied in some depth. It has been shown that the applications of this propulsion mode to a Halley rendezvous mission provides reasonable payloads and flight times without the use of Saturn-class launch vehicles.

Study of nuclear-electric rendezvous with Encke/90 indicates that payload can be doubled (with advanced technology) and flight time halved compared to impulsive ballistic results. Similar results can be expected for other short-period comet rendezvous opportunities

3.4 Solar-Electric Low-Thrust Mode

A solar-electric spacecraft employs solar cell arrays to derive the necessary power to operate the ion thrusters. This propulsion system has attained an advanced state of development with flight readiness projected to the post-1974 time period (Bartz and Horsewood, 1969). A propulsion system specific mass (α_{ps}) of 30 kg/kw (66 lbs/kw), including power and thrust

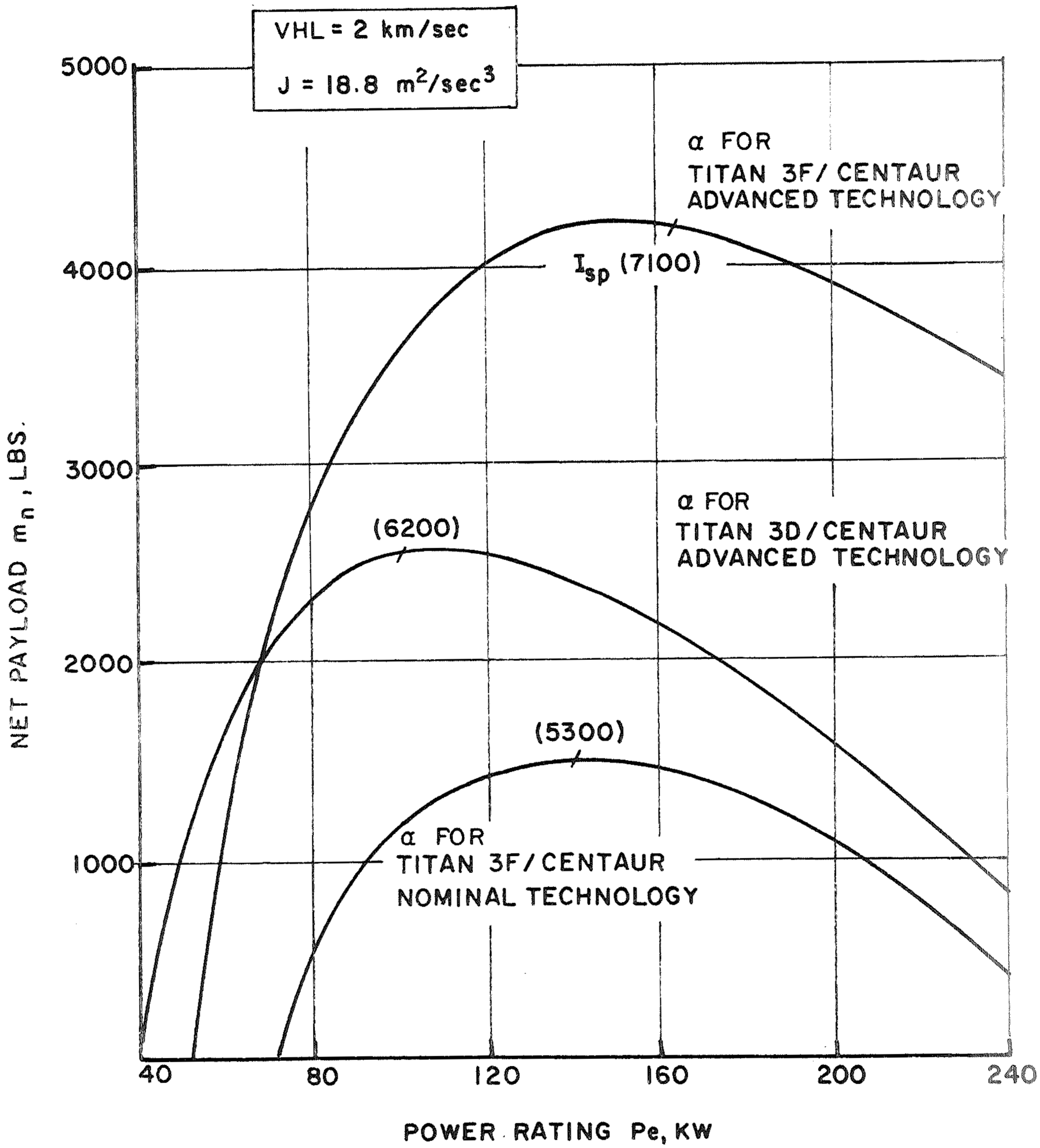

FIGURE 23 PAYLOAD CAPABILITY OF NUCLEAR-ELECTRIC SPACECRAFT FOR 500-DAY RENDEZVOUS MISSION TO COMET ENCKE, ARRIVAL 7/31/90

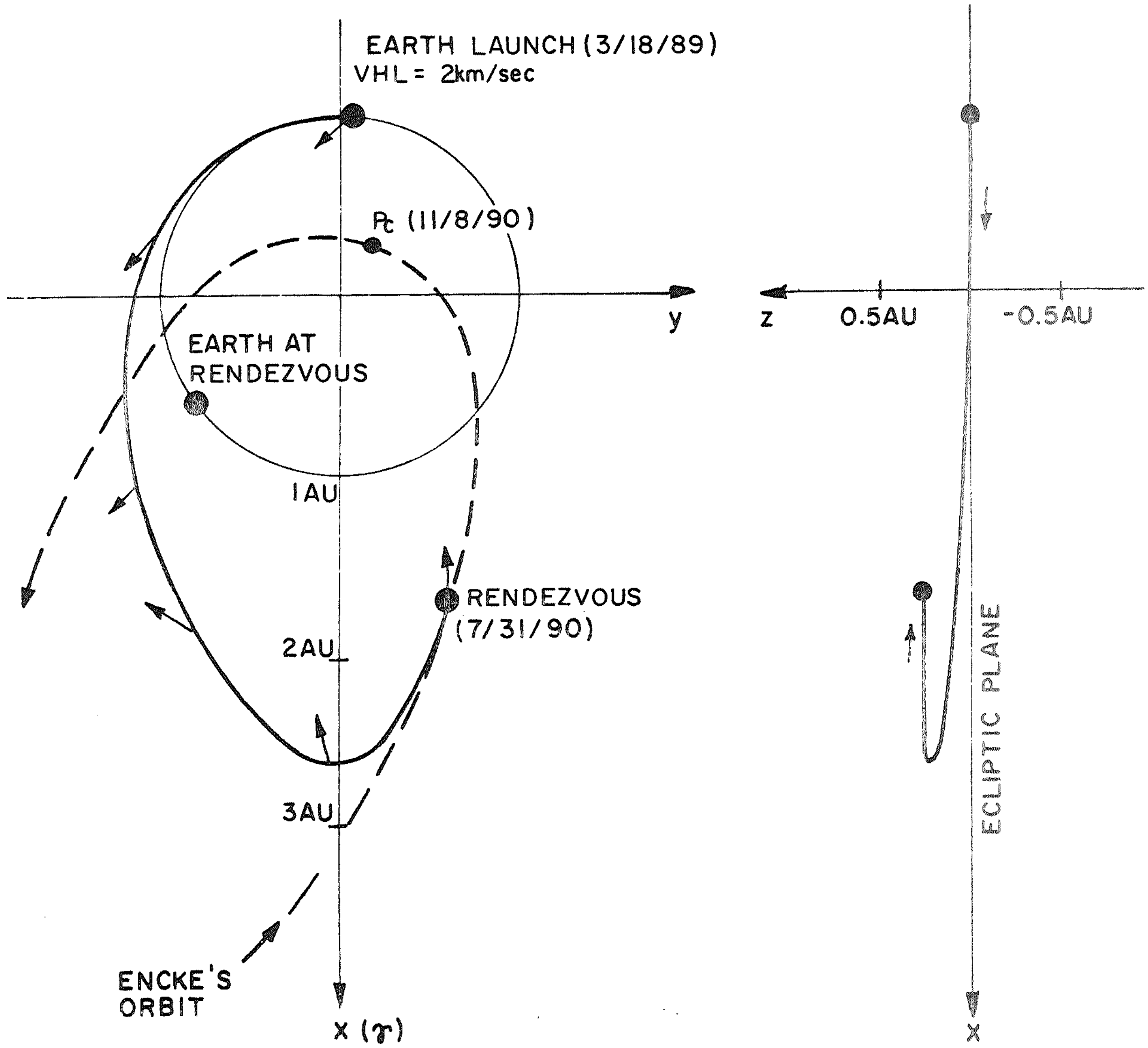

FIGURE 24. 500-DAY RENDEZVOUS TRAJECTORY TO COMET ENCKE/90, NUCLEAR-ELECTRIC LOW-THRUST FLIGHT MODE.

subsystems, appears to be a realistic design goal. The main disadvantage of solar power from a trajectory standpoint is the inherent fall-off of power with increasing distance from the sun. This tends to make the trajectory maneuvering capability less efficient for comet rendezvous than would be the case with constant power (nuclear-electric). Longer flight times will usually be required to compensate for this effect, i.e., to deliver the same payload. Still, the solar electric propulsion (SEP) mode can be expected to out-perform the ballistic flight mode because of the high specific impulse of the ion thrusters employed.

Some early work on SEP comet missions has been reported in the literature (Park, 1967). That study considered missions to the comets Temple-2, Encke and d'Arrest. The launch vehicle selection was the Atlas (SLV-3A)/Burner II and the science payload was 56 pounds. Flight times to each of the comets was about 1000 days. It is not clear whether the rendezvous trajectories were fully optimized, i.e., whether the flight times could be reduced significantly in delivering the same payload. Furthermore, the mission examples studied required launches in the early 1970's which is improbable now in light of current program planning. The present study examines the SEP flight mode in terms of launch opportunities, launch vehicles and payload requirements which are compatible with current mission planning.

Trajectory analysis was limited to several attractive comet opportunities as determined by the preceding ballistic mode results. Basically, these opportunities are Encke/80, d'Arrest/82 and Kopff/83. The purpose here is to compare the SEP performance with the better ballistic missions, thus allowing a reasonable basis for trade-off. Halley's Comet was also considered to determine whether or not the SEP mode is at all practical for this mission. The recently developed computer program CHEBYTOP (Hahn, 1969) was utilized for the trajectory and payload optimization. Low-thrust propulsion is initiated outside of the earth's sphere of influence after a high-thrust launch and injection to a specified hyperbolic excess velocity VHL. This velocity along with the initial power level P_o (at 1 a.u.) and constant specific impulse I_{sp} may be chosen so as to maximize the net spacecraft mass. Thrust direction and coast periods are also optimized. The solar power variation with distance from the sun is taken from an analysis by Strack (1966).

Figure 25 shows the region of optimum arrival dates in the vicinity of perihelion for constant flight time trajectories to Comet d'Arrest/82. Trajectory requirements are presented in terms of the energy parameter J* defined by

$$J^* = \int_0^{t_f} a^2(t) \frac{P_o}{P(t)} dt$$

where a(t) is the thrust acceleration, P(t) is the instantaneous power and t_f is the flight time. Different values of VHL cause a shifting of the curves up or down but generally have little effect on the optimum arrival date. For a propulsion system specific mass of 30 kg/kw, values of J* greater than about 15 m^2/sec^3 result in vanishing payload and, hence, are not of practical interest. Beginning with the high energy 800-day flight, one notes the nearly equal shifting of optimum arrival time with flight time. This reflects the fact that the optimum earth launch position is essentially fixed by the comet's orbital geometry. Also, for a given flight time such as 800 days, there are local minimum points separated by nearly one year. Relatively fast rendezvous flights of 300 or 400 days are possible, but these require a post-perihelion arrival. The generation of

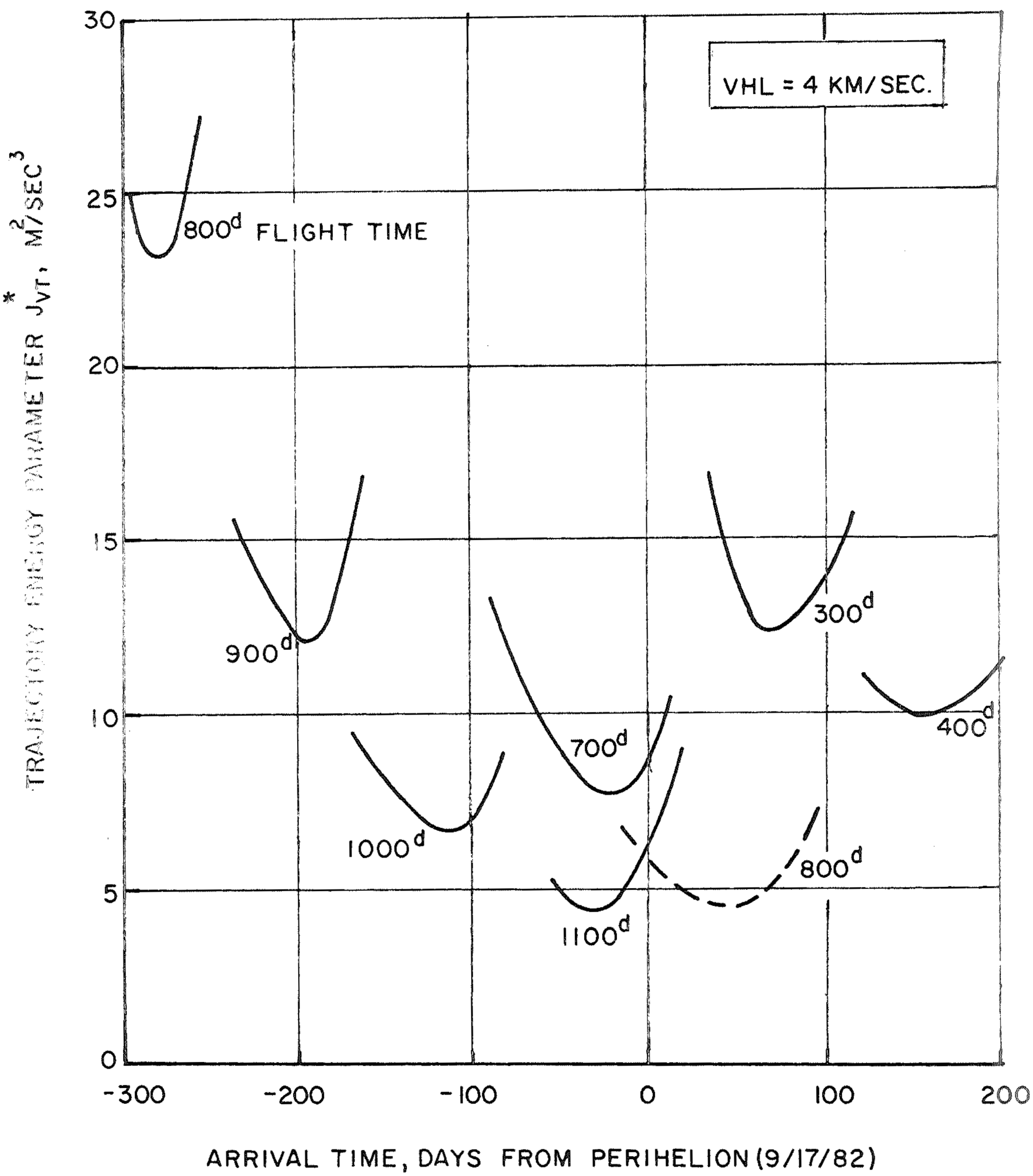

FIGURE 25. EFFECT OF ARRIVAL TIME ON TRAJECTORY REQUIREMENTS, SOLAR-ELECTRIC RENDEZVOUS WITH COMET d'ARREST/82

basic data maps such as Figure 25 are a useful first step in the selection of comet rendezvous trajectories for later, more detailed analysis payload optimization.

Figure 26 illustrates the ecliptic and out-of-plane trajectory profiles of the 700-day flight to d'Arrest arriving 20 days before the 1982 perihelion. In this case, a VHL of 3 km/sec is near-optimum for the Titan 3C launch vehicle. The spacecraft traverses almost a full revolution about the sun, reaches a maximum solar distance of about 2.4 au, and a maximum out-of-plane distance of 0.6 au. Figure 27 shows a 900-day flight to Comet Encke launched in 1978 near the comet orbit's major axis and arriving 104 days before the 1980 perihelion. A 700-day flight to Comet Kopff launched in 1981 and arriving 50 days before the 1983 perihelion is shown in Figure 28. It should be noted that the Kopff example trajectory is off-optimum for a 700-day flight in that the optimum arrival date is after perihelion.

Solar-electric propulsion might be expected to provide only marginal payload performance compared to nuclear-electric propulsion for the Halley rendezvous mission because the change from posigrade to retrograde motion is most efficiently made at large solar distances where the propulsion power available is greatly reduced. Figure 29 shows an example trajectory to Halley launched in 1978 and arriving 55 days before the 1986 perihelion. The spacecraft is 1 au below the ecliptic plane at an aphelion distance of 7.3 au when the momentum reversal begins. Although the power available at this point is only 1/25th of the initial power, a small value of thrust acceleration is effective in changing the trajectory because of the slow motion at this distance. The major drawback of this example is that the propulsion time required is a large fraction of the very long 7.5-year flight time.

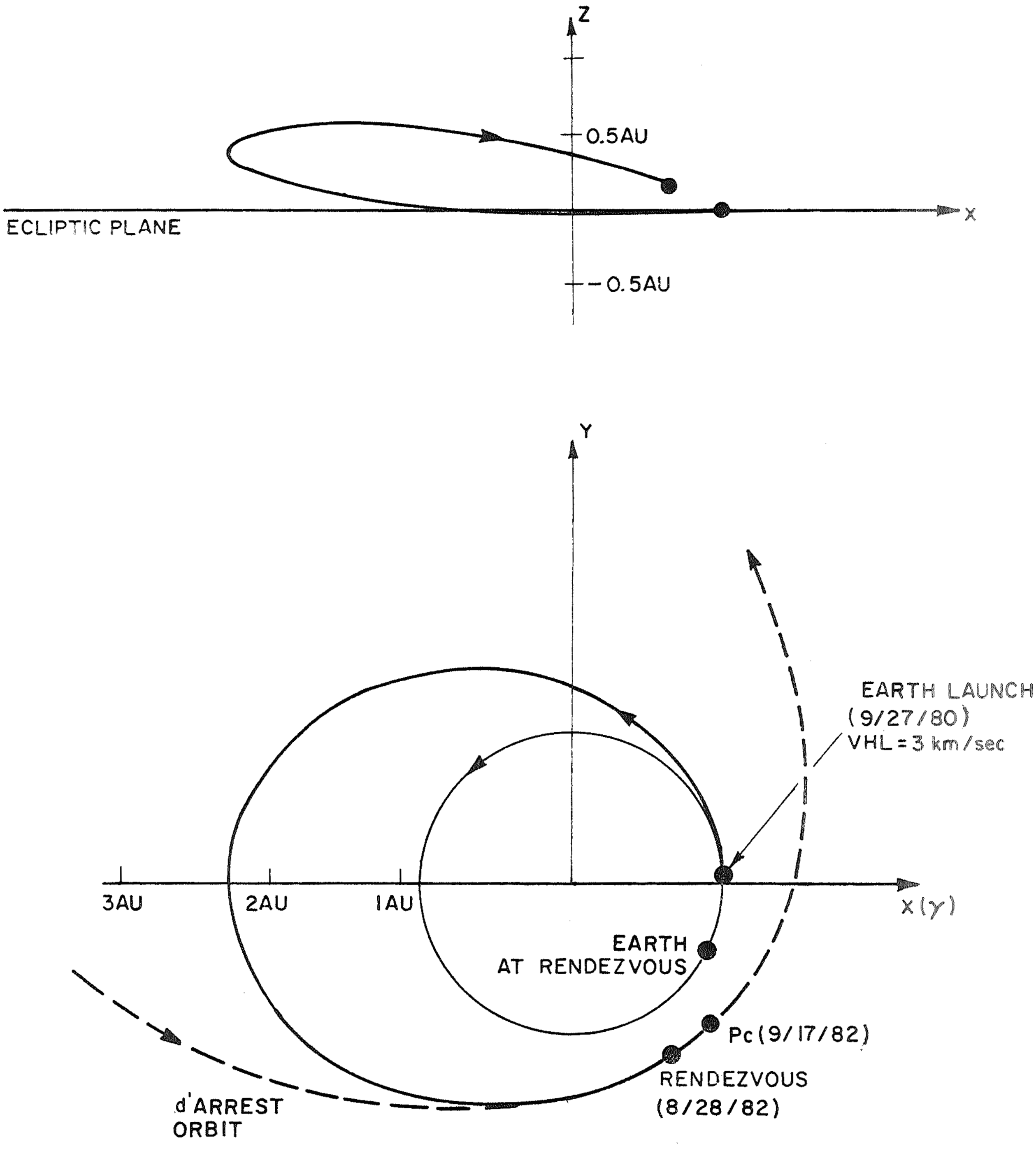

FIGURE 26. 700-DAY SOLAR-ELECTRIC RENDEZVOUS WITH COMET D'ARREST/82

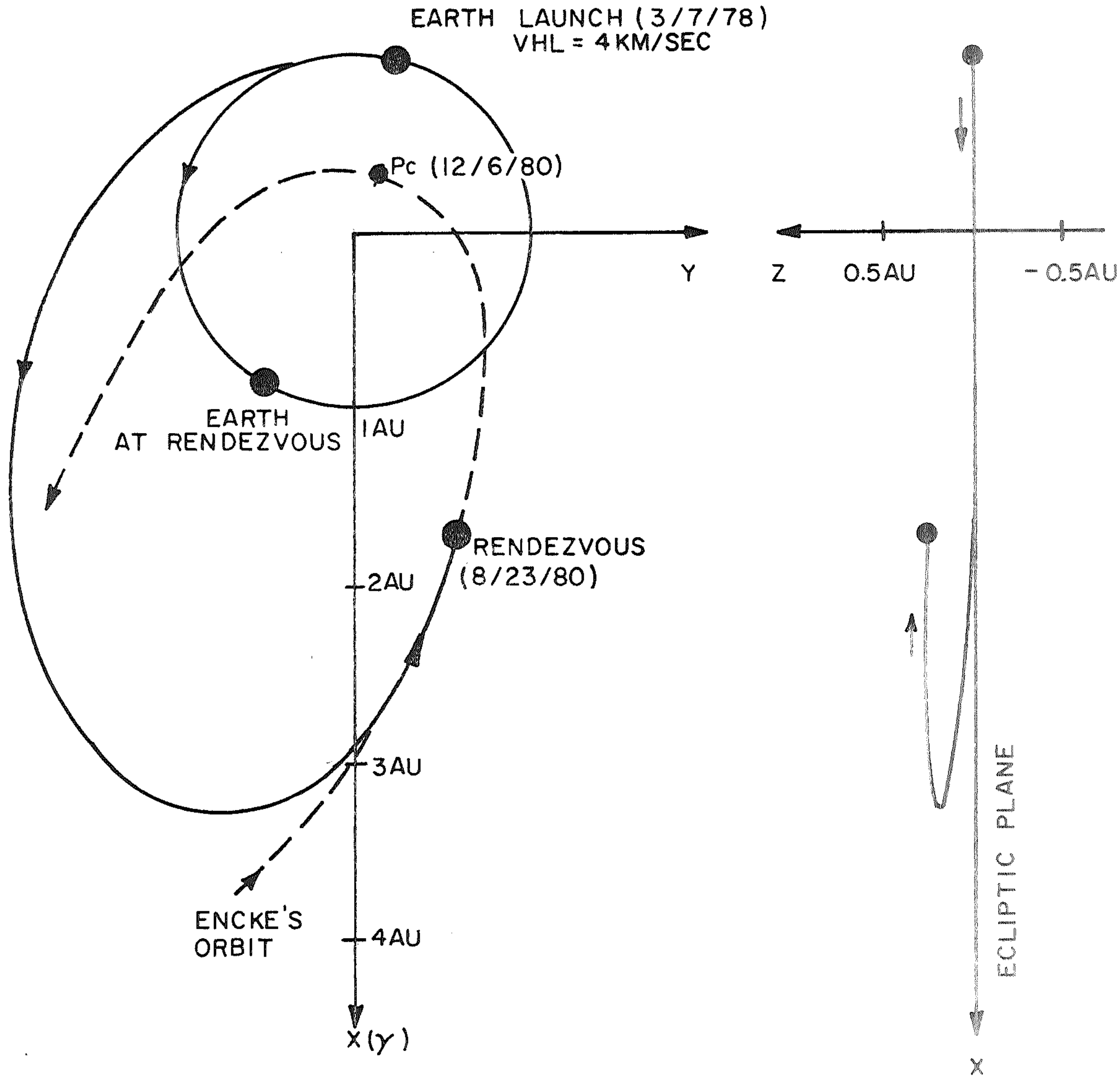

FIGURE 27. 900-DAY SOLAR-ELECTRIC RENDEZVOUS WITH COMET ENCKE/80

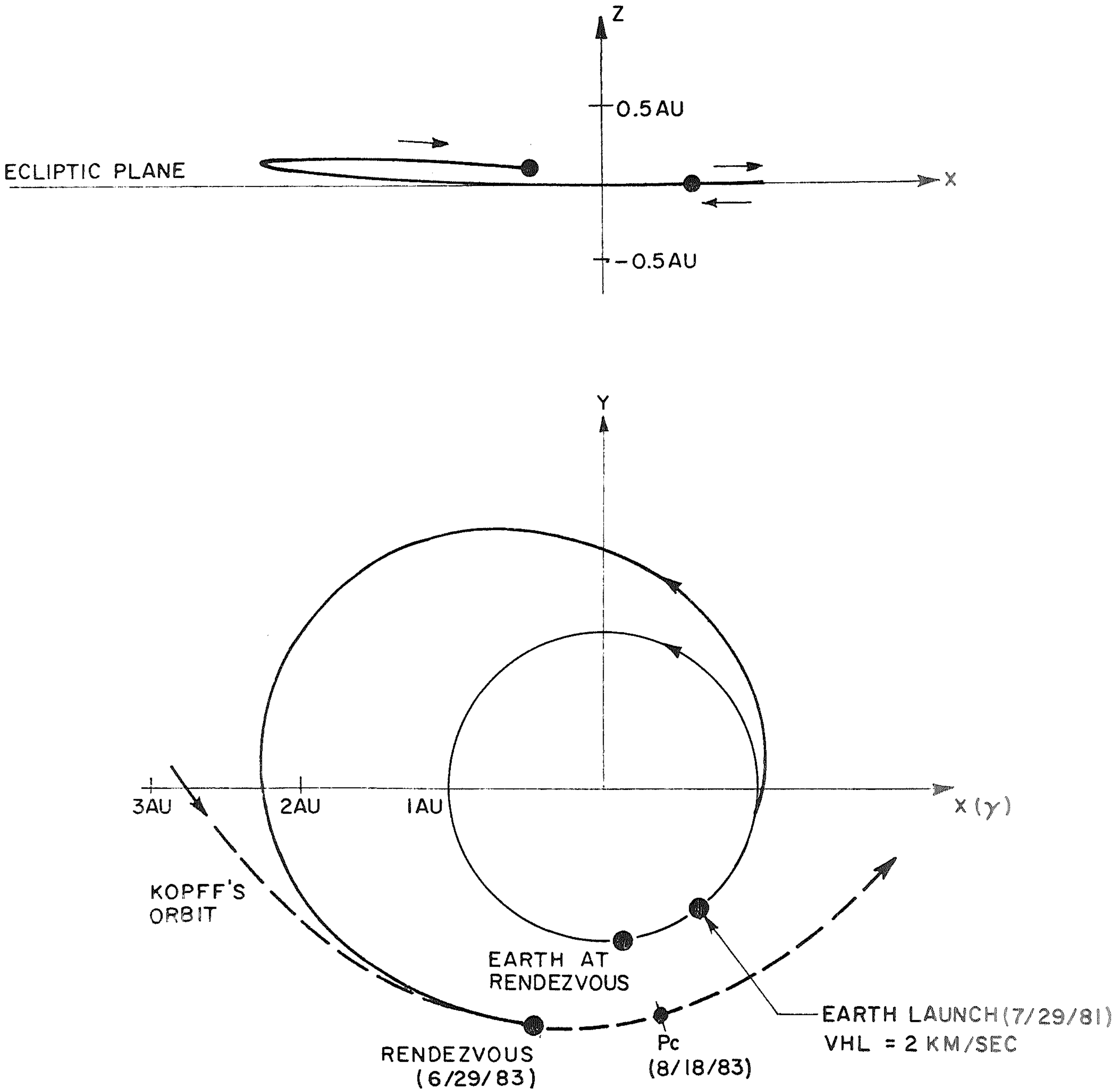

FIGURE 28. 700-DAY SOLAR-ELECTRIC RENDEZVOUS WITH COMET KOPFF/83

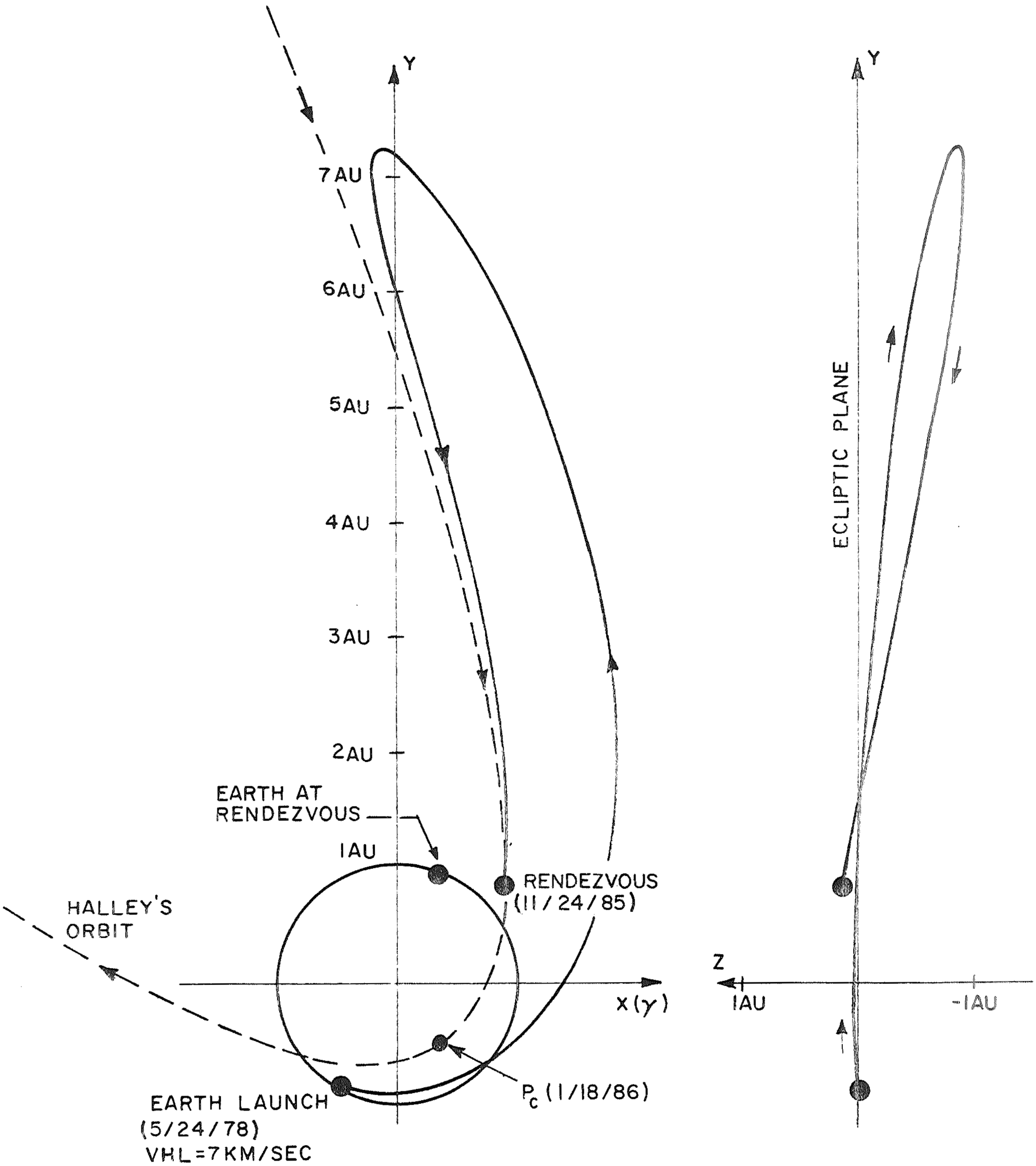

FIGURE 29. 2740-DAY SOLAR-ELECTRIC RENDEZVOUS WITH HALLEY'S COMET

Table 11 provides a summary of the SEP flight mode results obtained for the four comet missions investigated. Values listed for launch velocity, power and specific impulse are near-optimum for the given launch vehicle selections. Missions to Encke, d'Arrest, and Kopff are similar in that the flight times are under 2.5 years, the payload (net spacecraft mass) is about 1000 pounds, and the SEP spacecraft can be launched by the Titan 3C. Optimum propulsion power is 20-25 kw at a specific impulse of 3500 seconds. Because of similar orbital characteristics of many short-period comets, one may predict that the results of these three missions apply generally to a larger class of comet mission opportunities. The Halley mission is a special case and does not appear to be as attractive for SEP application. The Titan 3F/Centaur provides only a marginal payload of under 500 pounds, the power rating is high and the flight time is over 7 years.

Characteristics of net spacecraft weight as a function of power rating are shown in Figures 30 through 32 for the Encke/80, d'Arrest/82, and Kopff/83 missions. The Titan 3D/Centaur is considered in addition to the Titan 3C in order to ascertain whether significant payloads can be delivered utilizing relatively small solar arrays. For example, suppose P_o were limited to 15 kw which is a lower than optimum power for both launch vehicles -- very much so far for the Titan 3D/Centaur. The net weight capability of these two launch vehicles at P_o = 15 kw are compared below.

Mission	Titan 3C/ SEP (15 kw)	Titan 3D/Centaur/ SEP (15 kw)
Encke/80	925 lbs.	1320 lbs.
d'Arrest/82	825 lbs.	1015 lbs.
Kopff/83	660 lbs.	< 660 lbs.

TABLE II

SUMMARY OF SOLAR-ELECTRIC COMET RENDEZVOUS MISSIONS

MISSION PARAMETERS	ENCKE/80	d'ARREST/82	KOPFF/83	HALLEY/86
LAUNCH DATE	7 MARCH 1978	27 SEPT. 1980	29 JULY 1981	24 MAY 1978
LAUNCH VEHICLE	TITAN 3C	TITAN 3C	TITAN 3C	TITAN 3F/CENTAUR
LAUNCH HYPERBOLIC VELOCITY, KM/SEC	3	3	2	7
SEP PROPULSION SYSTEM*				
POWER RATING, KWE	20	20	25	50
SPECIFIC IMPULSE, SEC	3500	3500	3500	3500
ARRIVAL TIME, DBP	100	20	50	55
NET SPACECRAFT WEIGHT, LBS.	1015	910	1075	415
FLIGHT TIME, DAYS	900	700	700	2740

* FIXED PROPULSION SYSTEM PARAMETERS INCLUDE:

SPECIFIC POWERPLANT WEIGHT, α_{ps} = 66 LBS/KWE
EFFICIENCY, η = 66 %
TANKAGE WEIGHT FACTOR, K_t = 6 %

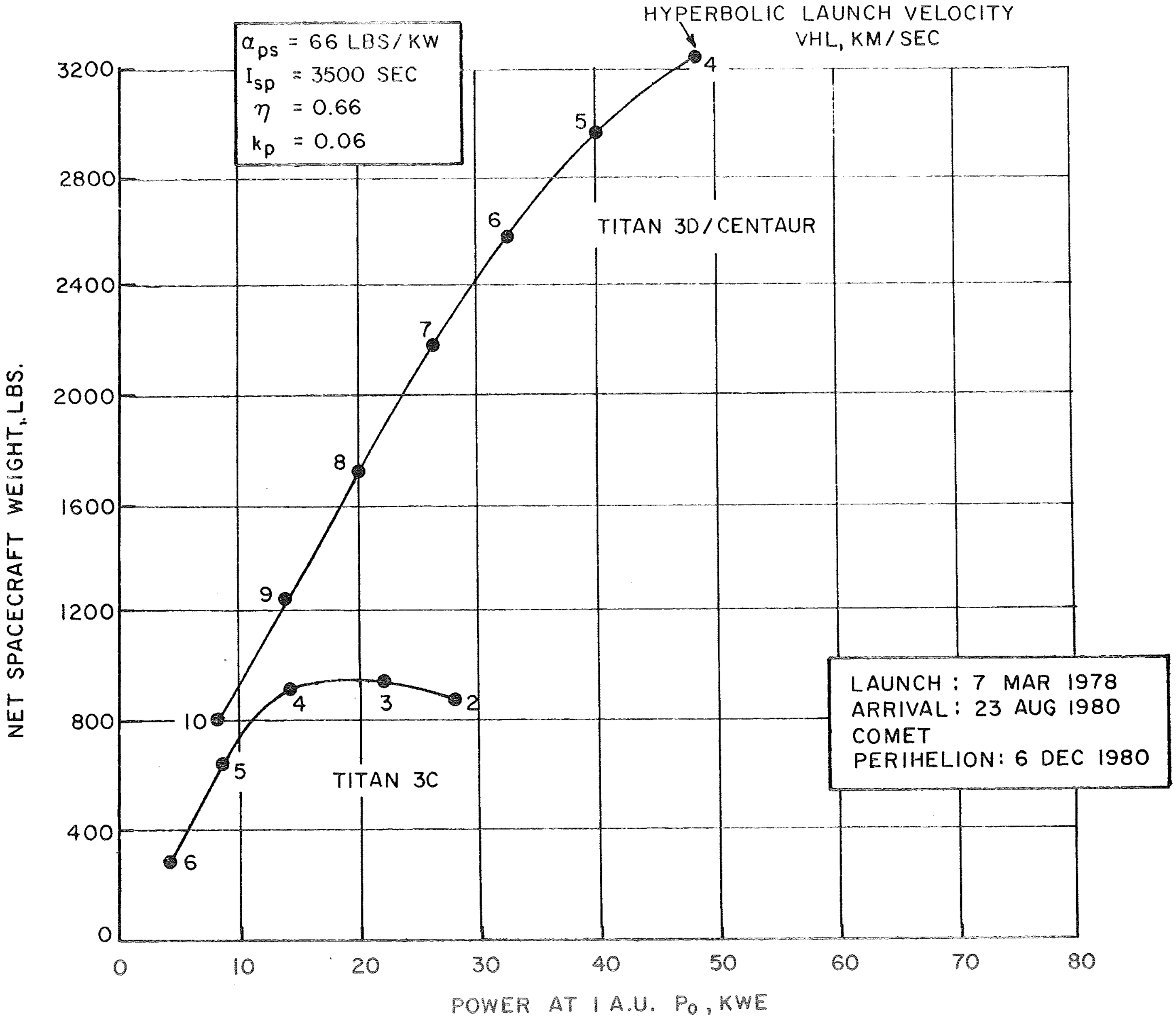

FIGURE 30. SOLAR-ELECTRIC PAYLOAD CAPABILITY FOR 900-DAY RENDEZVOUS TRAJECTORY TO COMET ENCKE/80

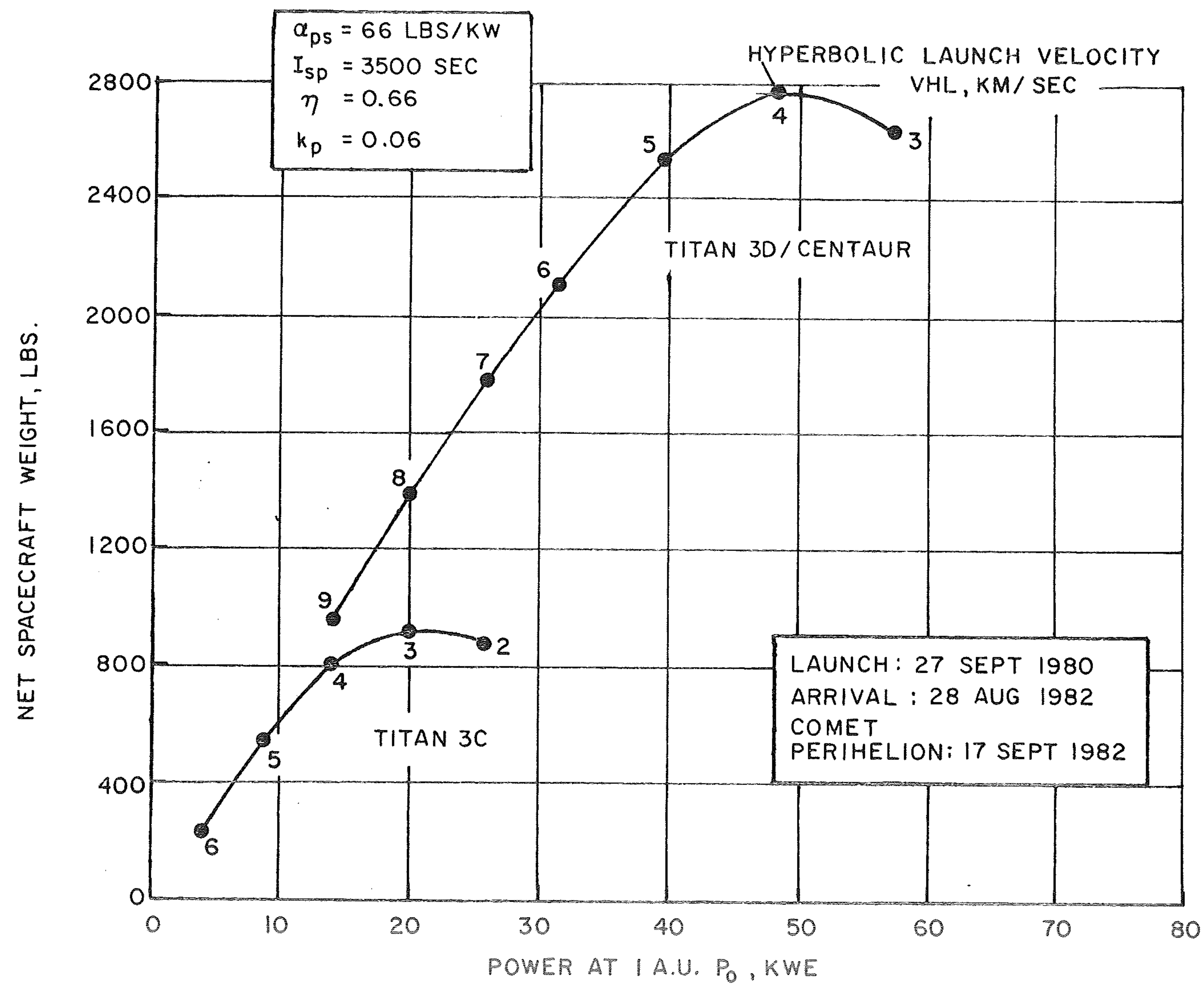

FIGURE 31. SOLAR-ELECTRIC PAYLOAD CAPABILITY FOR 700-DAY RENDEZVOUS TRAJECTORY TO COMET D'ARREST/82

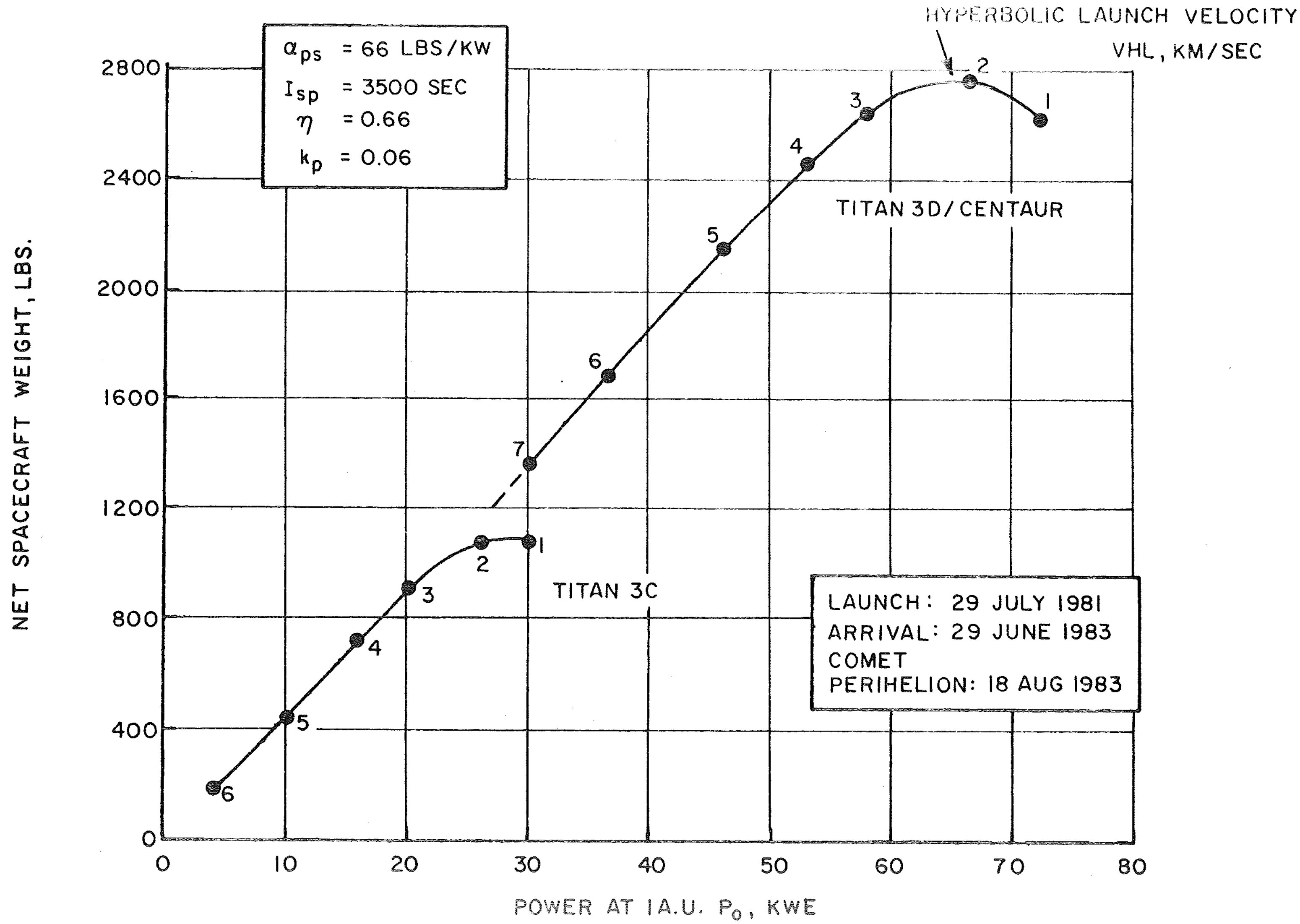

FIGURE 32. SOLAR-ELECTRIC PAYLOAD CAPABILITY FOR 700-DAY RENDEZVOUS TRAJECTORY TO COMET KOPFF/83

The larger launch vehicle offers a fair improvement in payload for the Encke and d'Arrest missions but none at all for the Kopff mission. These numbers are only illustrative of the trade-off that can be made in mission design studies. A final design selection would depend upon many factors including science payload requirements and launch vehicle and spacecraft costs.

In the previous discussion of Figure 26 it was mentioned that a short flight time rendezvous with d'Arrest is possible if a post-perihelion arrival is acceptable. This result motivated us to examine the d'Arrest 1976 opportunity which is currently under consideration as a ballistic intercept (fast flyby) mission utilizing the Atlas/Centaur launch vehicle and a flight time of about 100 days. As a possible but more expensive alternative, a 280-day SEP rendezvous mission is considered here. This mission would be launched in early 1976 near the comet's ascending node and arrive 100 days after the perihelion of August 13, 1976. The trajectory profile is illustrated in Figure 33. During the first half of the flight the spacecraft remains near 1 a.u. while traversing a path out of the ecliptic plane to match the comet's inclination of 17°. At a point 10 days after perihelion (90 days before actual rendezvous), the spacecraft is about 14×10^6 km from d'Arrest and closing with a relative velocity of about 3.5 km/sec. Figure 34 shows the payload capability of the Titan 3C and Titan 3D/Centaur launch vehicles as a function of power rating. In this case the specific impulse was fixed at 3000 seconds, which is closer to optimum for this mission than the 3500 second value used above. The maximum payload capability of the Titan 3C is 550 pounds at a SEP power rating of about 23 kw. The payload decreases to 470 pounds at the off-optimum power of 15 kw. At 15 kw, the Titan 3D/Centaur launch vehicle would have a payload capability

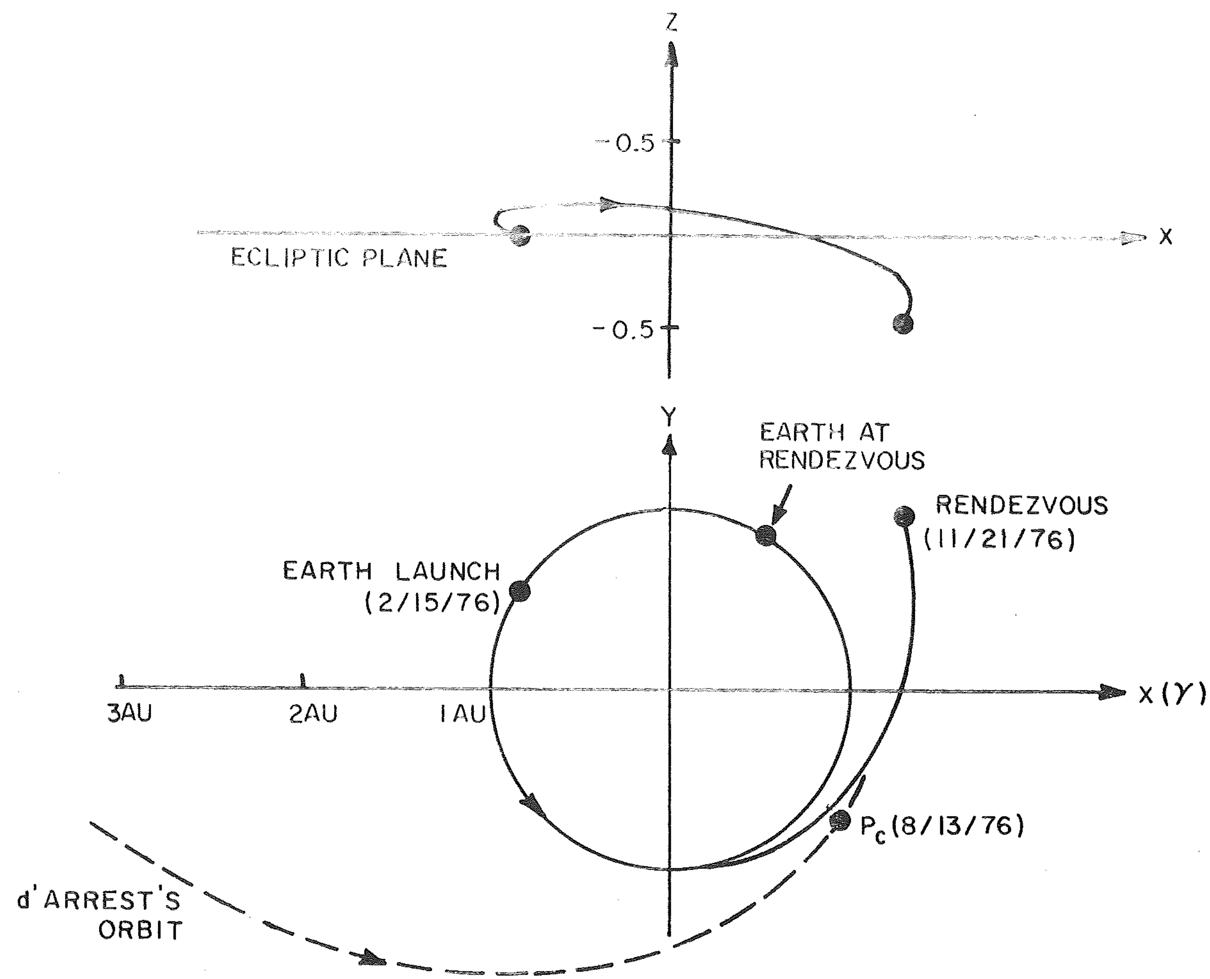

FIGURE 33. SOLAR-ELECTRIC RENDEZVOUS WITH COMET d'ARREST/76

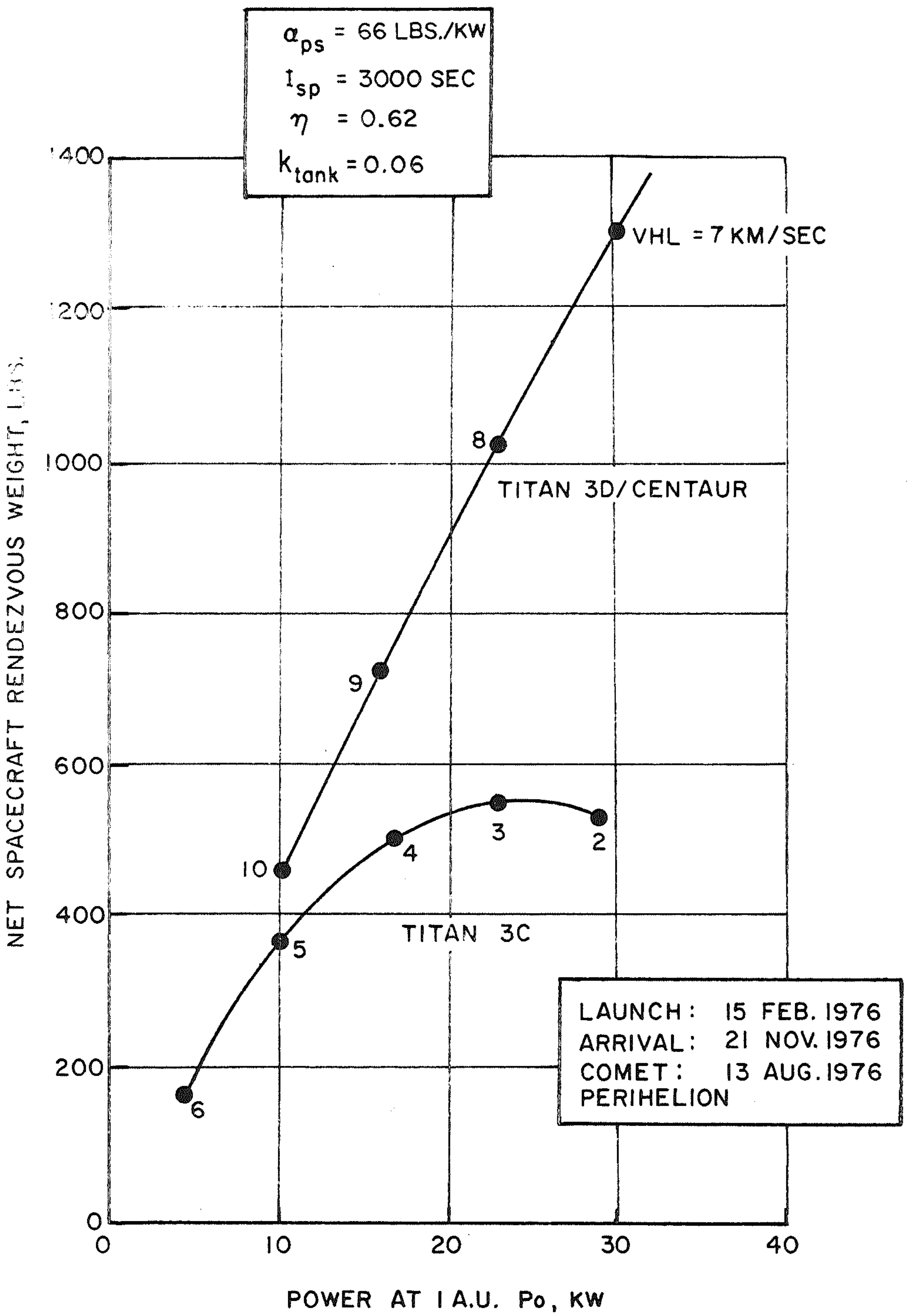

FIGURE 34. SEP PAYLOAD CAPABILITY FOR 280-DAY RENDEZVOUS TRAJECTORY TO COMET D'ARREST/76

of 675 pounds. The d'Arrest/76 mission opportunity has been included here more as an example of fast rendezvous than as a suggested mission. The early launch date and post-perihelion arrival probably precludes this SEP mission from serious consideration.

4. FLIGHT MODE COMPARISONS

In Section 3 of this report, the payload/flight time characteristics of rendezvous opportunities to comets with good sighting conditions were considered according to the four flight modes studied. The primary objective of this report is to identify for further study comet rendezvous opportunities which are potentially applicable to a comet exploration program culminating in a Halley rendezvous mission during the 1986 apparition. In this section payload, flight time and launch vehicle requirements of the different flight modes which have been considered are compared for the following comet apparitions: Encke/80, d'Arrest/82, Kopff/83 and Halley/86. Rendezvous results for other comet apparitions such as Temple-2/88 and Forbes/93 are worth noting, but because the opportunities for these missions occur after 1985 they will not be discussed further at this time.

4.1 Rendezvous With Encke/80 (90)

The position of earth and comet Encke during the 1980 and 1990 apparitions are essentially the same. Hence, the following comparisons for the 1980 apparition apply to the 1990 apparition as well.

The flight time for a ballistic multi-impulse (MI) rendezvous with Encke is 3.5 years (see Figure 35) which places the launch opportunity in February 1977. Two impulses totaling 3.85 km/sec must be performed following earth launch. A multi-burn space-storable propulsion stage weighing about 4430 pounds would be necessary to perform these maneuvers with a 1000 pound spacecraft payload. A Titan 3F/Centaur launch vehicle is required.

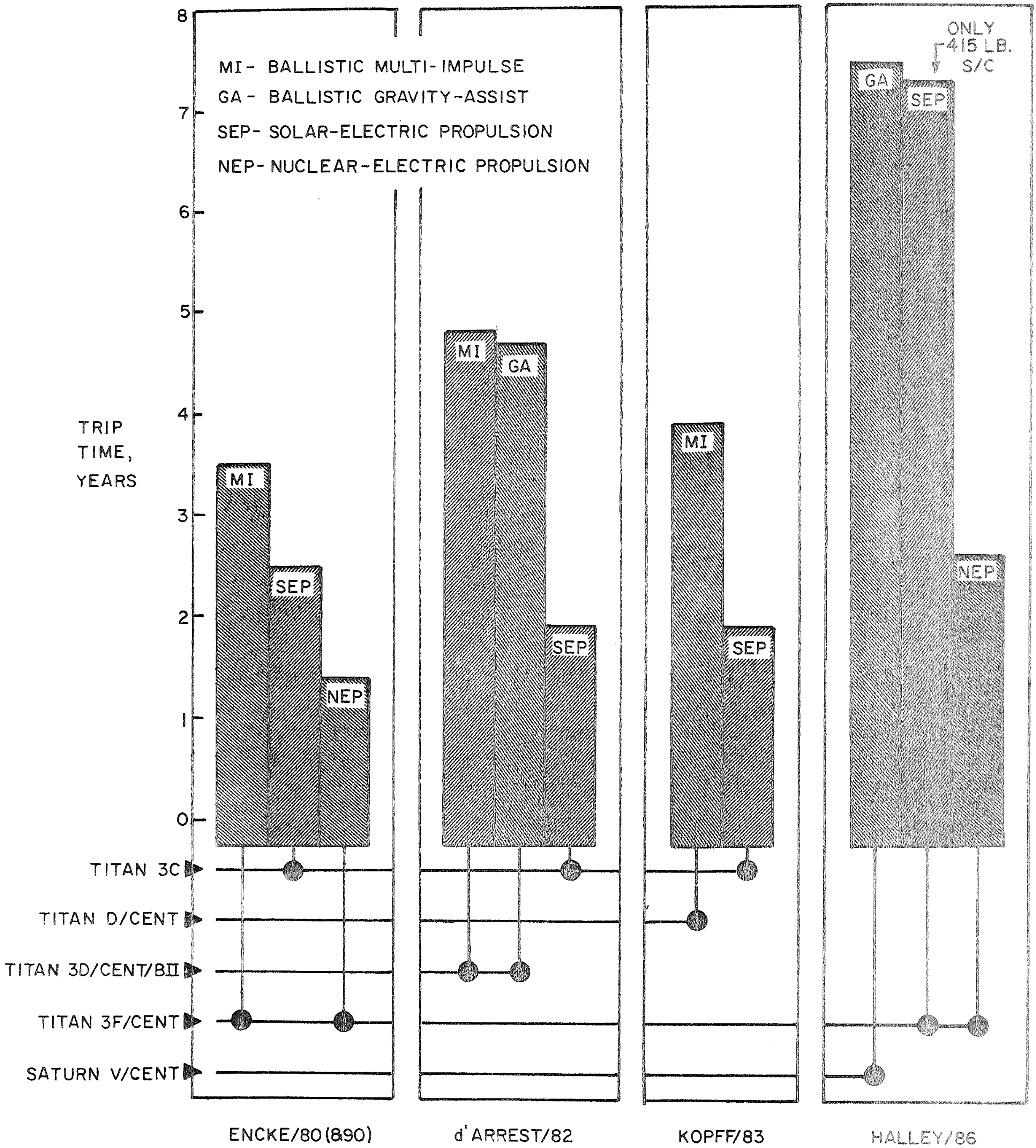

FIGURE 35. COMET FLIGHT MODE COMPARISONS FOR ~1000 LB. RENDEZVOUS SPACECRAFT

Both flight time and launch vehicle are reduced if solar-electric propulsion (SEP) is substituted for the multi-impulse flight mode. A flight time of 2.5 years represents a one-year saving in time to rendezvous. With a solar-electric stage rated at 15 kw power at 1 au (non-optimum) a Titan 3C vehicle delivers 925 pounds payload to rendezvous with Encke. Adding a Centaur stage (Titan 3D/Centaur) raises the payload at the same off-optimum power level to 1320 pounds, or for 1000 pounds payload further reduces the power rating to 10.5 kw at 1 au.

Another year of flight time can be saved by advancing to nuclear-electric propulsion (NEP) and retaining the Titan 3F/Centaur. However, the wisdom of developing such an advanced high-energy propulsion system to gain one year advantage in flight time is questionable. Hence, it is concluded that the solar-electric low-thrust flight mode represents the best compromise between mission characteristics (flight time, payload and launch vehicle) and necessary propulsion development for an Encke rendezvous mission.

4.2 Rendezvous With d'Arrest/82

A three-impulse ballistic rendezvous mission to d'Arrest takes about 4.8 years from launch. The launch opportunity occurs in August of 1977 with rendezvous occurring about 100 days before perihelion. A 2930 pound multi-burn space-storable stage will perform the necessary post-launch maneuvers with a 100 pound spacecraft payload. A Titan 3D/Centaur/Burner II launch vehicle is required.

A Jupiter gravity assist (GA) is possible for rendezvous during d'Arrest's 1982 apparition. However, no significant differences in over-all mission performance compared to the multi-impulse (MI) flight mode are evident, as can be verified by reviewing Figure 35. The flight is reduced about one month and the launch vehicle is unchanged. There are, however, significant design differences in the propulsion requirements of the two ballistic flight modes (MI and GA). With a Jupiter gravity assist the largest impulse (2.2 km/sec) does not occur until rendezvous, i.e., at the very end of the transfer flight. There are reliability and guidance problems suggested by this situation as well as the Jupiter-assist which would have to be studied to assess whether this flight mode is comparable to ballistic multi-impulse.

Going to solar-electric low-thrust propulsion (SEP) provides impressive advantages over either of the ballistic modes. A 2.8-year savings in flight time is possible with a Titan 3C launch vehicle delivering slightly less than 1000 pounds payload at optimum power (22 kw). Using an off-optimum power rating of 15 kw at 1 au requires a Titan 3D/Centaur to rendezvous 1000 pounds payload in 1.9 years. The launch date, in September 1980, occurs about three years later than either ballistic flight mode. The arrival date is late, just 20 days before perihelion. The effect of an earlier arrival date on payload capability needs to be investigated. The 60% reduction in flight time would seem to be ample justification for preference of a solar-electric stage to a space-storable chemical stage even if the Titan 3D/Centaur is needed in either instance.

4.3 Rendezvous With Kopff/83

A ballistic multi-impulse transfer will rendezvous 1000 pounds payload with Kopff in about 3.9 years. The multiburn space-storable stage needed for the post-launch maneuvers weighs about 3280 pounds. The launch would take place in July 1970 and rendezvous accomplished 85 days before the 1983 perihelion. A Titan 3D/Centaur launch vehicle is required. Viewed from the standpoint of flight time and propulsion requirements, this is the easiest ballistic opportunity of the four comet rendezvous missions being discussed.

The flight time for the solar-electric flight mode is 1.9 years or about 2 years less than the ballistic multi-impulse flight mode. A 1000 pound payload can be delivered with the Titan 3C launch vehicle but the power rating at 1 au may be somewhat high at 22 kw. Unlike the previous cases discussed a larger launch vehicle does not decrease the required power rating for a 1000 pound payload mission. It would probably be necessary to increase the flight by one year in order to get the power down to the more acceptable level of 15 kw for a first-generation SEP stage design. This would, in turn, diminish the flight time advantage of the SEP flight mode by 50%. Another problem area is the fact that maximum payload is achieved at dates after perihelion for the cases studied. In order to provide a more compatible mission profile with envisioned science objectives, the arrival date had to be constrained to occur 50 days before the comet's perihelion.

Hence, further study of the solar-electric low-thrust trajectory characteristics for a Kopff/83 rendezvous will be necessary before a thorough comparison with the ballistic flight mode can be made. It can be concluded, however, that either flight mode is attractive compared with the other comet missions considered.

4.4 Rendezvous With Halley/86

The long flight time (> 7 years) required for a Halley/86 rendezvous mission with either the ballistic Jupiter gravity-assisted flight mode (GA) or the solar-electric low-thrust mode (SEP) may be enough to eliminate them from further consideration. The opportunities for these flight modes occur in 1977 and 1978 which would place either mission in direct competition with the outer planet Grand Tour Program for project funds. The added factors of a Saturn V/Centaur launch vehicle and a 9350 pound two-stage space-storable rendezvous stage for the GA mode or a seven-segment Titan and a 50 kw power system (rated at 1 au) for the SEP mode make these possibilities seem even more dismal.

To date the nuclear-electric propulsion (NEP) flight mode has been the only reasonable alternative for a Halley rendezvous. The required flight is 2.6 years, which for a rendezvous at 55 days before perihelion places the launch date in April 1983. Predictions indicate that this is probably early for a nuclear-electric capability at its current rate of development but not unreasonable if such a program could be accelerated. The nuclear-electric stage is sized at 140 kw with the power system weight based on a nominal level of technology. The launch vehicle required is the Titan 3F/Centaur, which is an additional development requirement. If the Titan 3D/Centaur were used the flight would increase to 3.5 years moving the launch date to the early summer of 1982. This would, of course, leave even less time for the development of the nuclear-electric stage and require it to operate about one year longer in space.

In summary, a nuclear-electric powered low-thrust flight mode is definitely the most promising alternative for rendezvous with Halley. It is, therefore, important now to determine whether the required hardware can be developed in time for an operational launch in 1982 or 1983. If, after thorough consideration it appears that this is an unreasonable goal, then other Halley mission alternatives, such as multiple hypervelocity (50 - 70 km/sec) flyby probes or a larger slow flyby ($\sim$ 6 km/sec) probe, should be seriously considered so that this valuable opportunity in comet exploration is not missed by default.

5. CONCLUSIONS AND RECOMMENDATIONS

It is concluded from the results which have been presented that a number of opportunities exist during the period 1975-2000 for performing comet rendezvous missions with 1000 pounds payload. At least 10 favorable opportunities have been identified utilizing the ballistic flight mode. Three impulses or two impulses plus a Jupiter gravity-assist are required. Either the Titan 3D/Centaur or Titan 3F/Centaur launch vehicles must be combined with a near state-of-the-art post-launch multi-burn space-storable stage to deliver 1000 pounds or more payload to rendezvous. Flight times range from 3 to 5 years.

Low-thrust flight modes, restricted to solar-electric propulsion until the mid-1980's, offer the best performance for comet rendezvous mission opportunities. Flight times, for those cases studied, were found to range from 1.5 to 3 years. Launch vehicles needed for solar-electric powered missions carrying 1000 pounds payload include the Titan 3C and the Titan 3D/ Centaur, the latter being preferred for an off-optimum power rating of about 15 kw which is consistant with current solar-electric stage design proposals.

It would appear at this time that practical accomplishment of a Halley rendezvous mission will depend primarily on the availability of a nuclear-electric low-thrust stage by 1983. Other flight modes, such as low-thrust combined with Jupiter gravity-assist, should continue to receive attention with shorter flight times (< 5 years) and Titan-class launch vehicles being the requirement objectives.

It is recommended that the four comet opportunities discussed in Section 4 -- Encke/80, d'Arrest/82, Kopff/83 and Halley/86 -- form the scope of consideration of the comet rendezvous mission study by Astro Sciences to follow this work.

The mission study will investigate several key areas relating to objectives, operations and performance. These areas are as follows:

1) Science objectives and measurement definitions; the new ingredient here is long term "in-situ" experiments in a dynamic environment,

2) Navigation and guidance; comet orbit determination accuracy is the key input,

3) Rendezvous operations; stationkeeping, maneuverability and science instrument profile,

4) Trajectory/hardware interface; launch and arrival windows, off-optimum parameter effects, etc.,

5) Spacecraft subsystem requirements; estimates of weight, power, data rate, etc.

In addition to the objectives outlined above, the study should determine which of the first three opportunities is the best multi-impulse ballistic mission and which is the best solar-electric low-thrust mission. The terminology "best" should be interpreted to mean the most compatible mission requirements for propulsion system design and development without sacrifice to the desired payload, flight time and arrival date characteristics. For the Halley/86 rendezvous opportunity additional analysis of hybrid trajectories as well as the nuclear-electric low-thrust flight mode should be performed.

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APPENDIX

SIGHTING AND ORBITAL DATA FOR SELECTED (GOOD LIST)

COMET APPARITIONS

This appendix consists of three figures and one table of data for each of the 16 comet apparitions with good earth-based sighting characteristics given in Table 1, Section 2. The first two graphs for each comet apparition (figures a and b) contain sighting data as defined in Section 2. The third figure (c) is an illustration of the comet's orbit rotated into the ecliptic plane. Positions of the earth are indicated at various perihelion passage dates of the comet. The table of data for each comet apparition contains time projections of the osculating elements of the comet's orbit, obtained by integrating the combined gravitational acceleration due to the sun and planets. No allowance has been made for secular perturbations. For some apparitions in the 1990's, where numerically integrated data had not been generated, the T_p (perihelion passage dates) were found by cubic extrapolation.

The data are presented in ascending order of comet perihelion dates as follows:

A-1.	Encke/80	A-9.	Temple-2/88
A-2.	d'Arrest/82	A-10.	Faye/91
A-3.	Grigg-Skjellerup/82	A-11.	Forbes/93
A-4.	Kopff/83	A-12.	Schaumasse/93
A-5.	Encke/84	A-13.	Tuttle/94
A-6.	Giacobini-Zinner/85	A-14.	Perrine-Mrkos/95
A-7.	Halley/86	A-15.	Kopff/96
A-8.	Borrelly/87	A-16.	Giacobini-Zinner/98

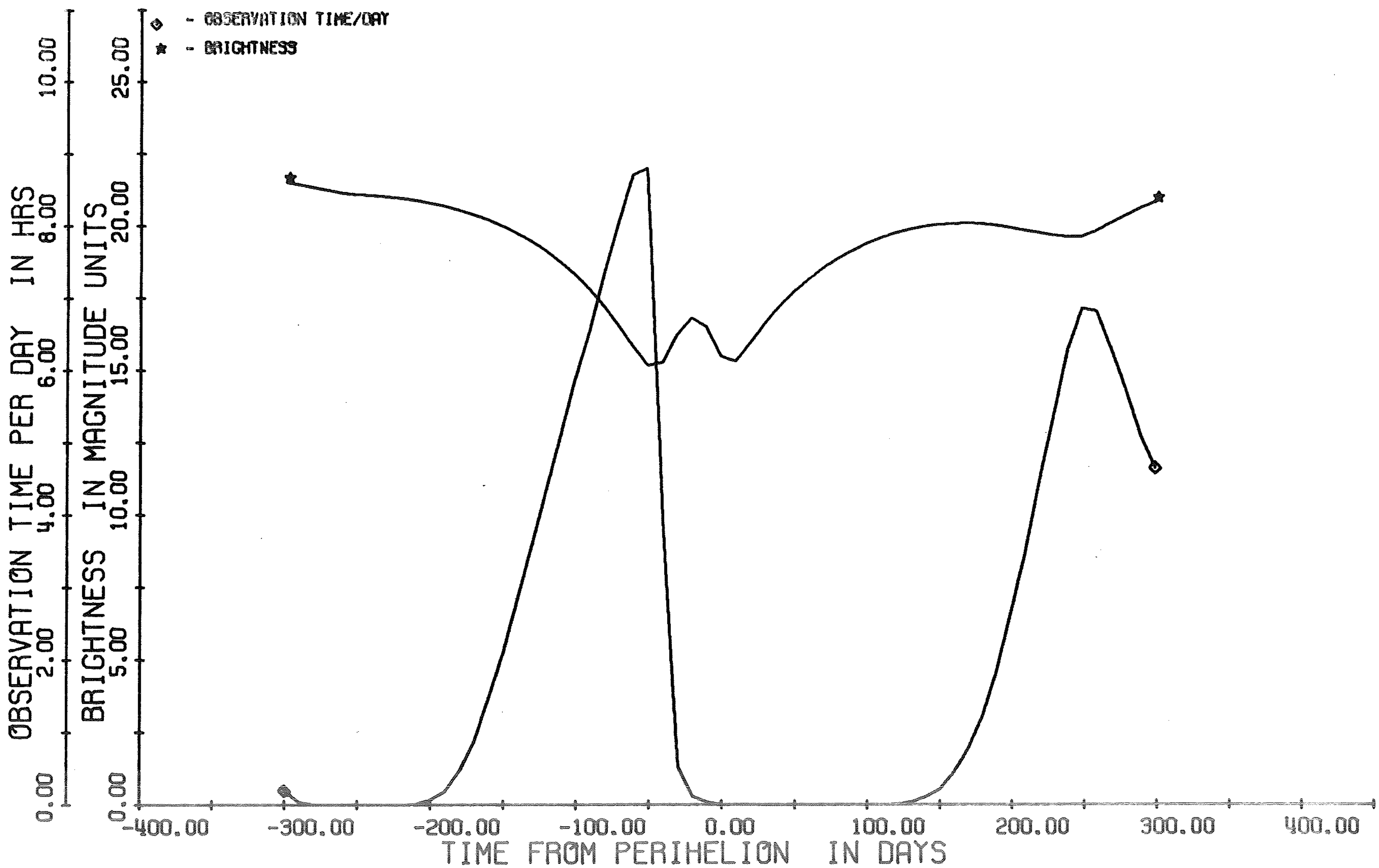


FIG A-Ia. SIGHTING CONDITIONS FOR ENCKE/80

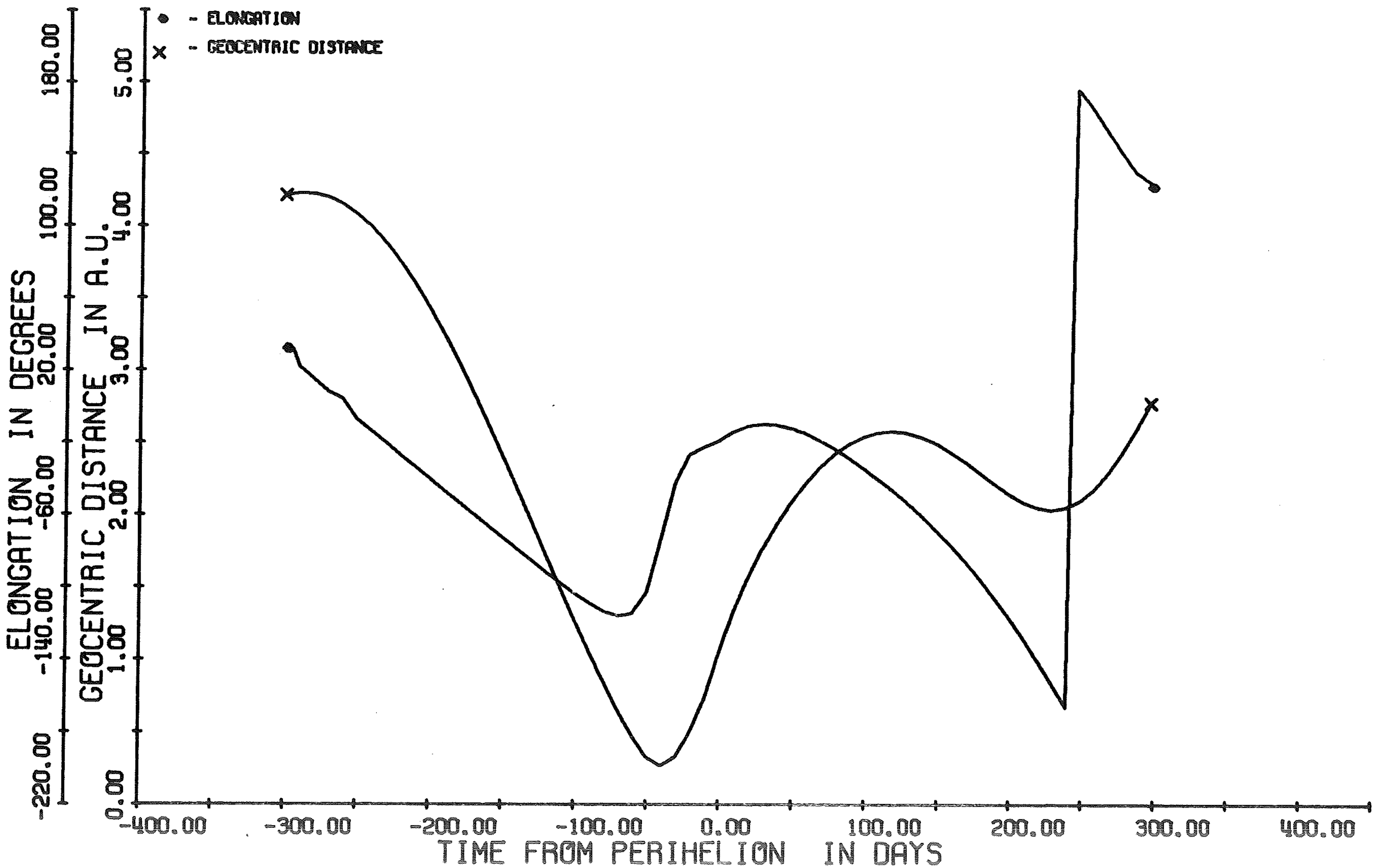
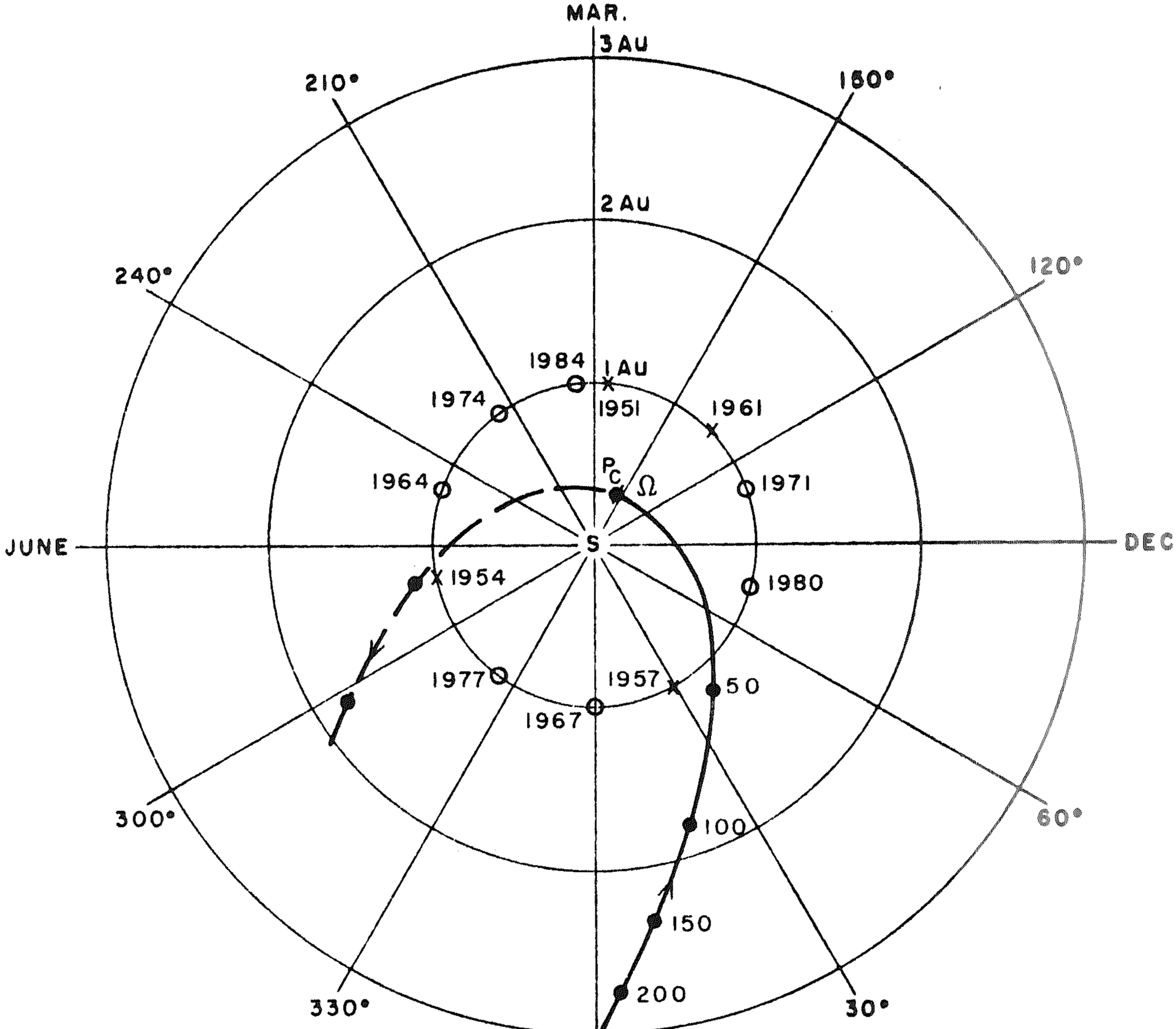


FIG A-1b. DISTANCE & ELONGATION FOR ENCKE/80

ENCKE



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-1c

TABLE A-1

OSCULATING ORBITAL ELEMENTS FOR COMET ENCKE

Epoch Calendar	Epoch Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
6/4/64	2,438,550.5	2.217	0.847	11.97	334.23	185.91	9/22/67
1/24/66	2,439,150.5	2.217	0.847	11.97	334.23	185.91	9/21/67
9/16/67	2,439,750.5	2.217	0.847	11.99	334.23	185.92	9/21/67
4/3/68	2,439,950.5	2.217	0.847	11.99	334.23	185.92	1/9/71
11/24/69	2,440,550.5	2.217	0.847	11.98	334.23	185.94	1/9/71
12/29/70	2,440,950.5	2.217	0.847	11.97	334.21	185.95	1/9/71
7/17/71	2,441,150.5	2.217	0.847	11.97	334.21	185.95	4/29/74
3/8/73	2,441,750.5	2.217	0.847	11.98	334.21	185.93	4/28/74
4/12/74	2,442,150.5	2.217	0.847	11.98	334.22	185.93	4/28/74
10/29/74	2,442,350.5	2.217	0.847	11.98	334.22	185.94	8/16/77
6/20/76	2,442,950.5	2.218	0.847	11.94	334.22	185.96	8/16/77
7/25/77	2,443,350.5	2.219	0.847	11.94	334.21	185.96	8/16/77
2/10/78	2,443,550.5	2.219	0.847	11.94	334.20	185.96	12/6/80
10/3/79	2,444,150.5	2.219	0.847	11.95	334.20	185.96	12/6/80
11/6/80	2,444,550.5	2.218	0.847	11.95	334.19	185.98	12/6/80
5/25/81	2,444,750.5	2.218	0.847	11.94	334.19	185.99	3/27/84
1/15/83	2,445,350.5	2.219	0.846	11.93	334.19	186.00	3/27/84
2/19/84	2,445,750.5	2.219	0.846	11.93	334.18	186.00	3/27/84
9/6/84	2,445,950.5	2.219	0.846	11.93	334.17	186.00	7/18/87
11/30/85	2,446,400.5	2.217	0.848	11.98	334.15	185.97	7/17/87

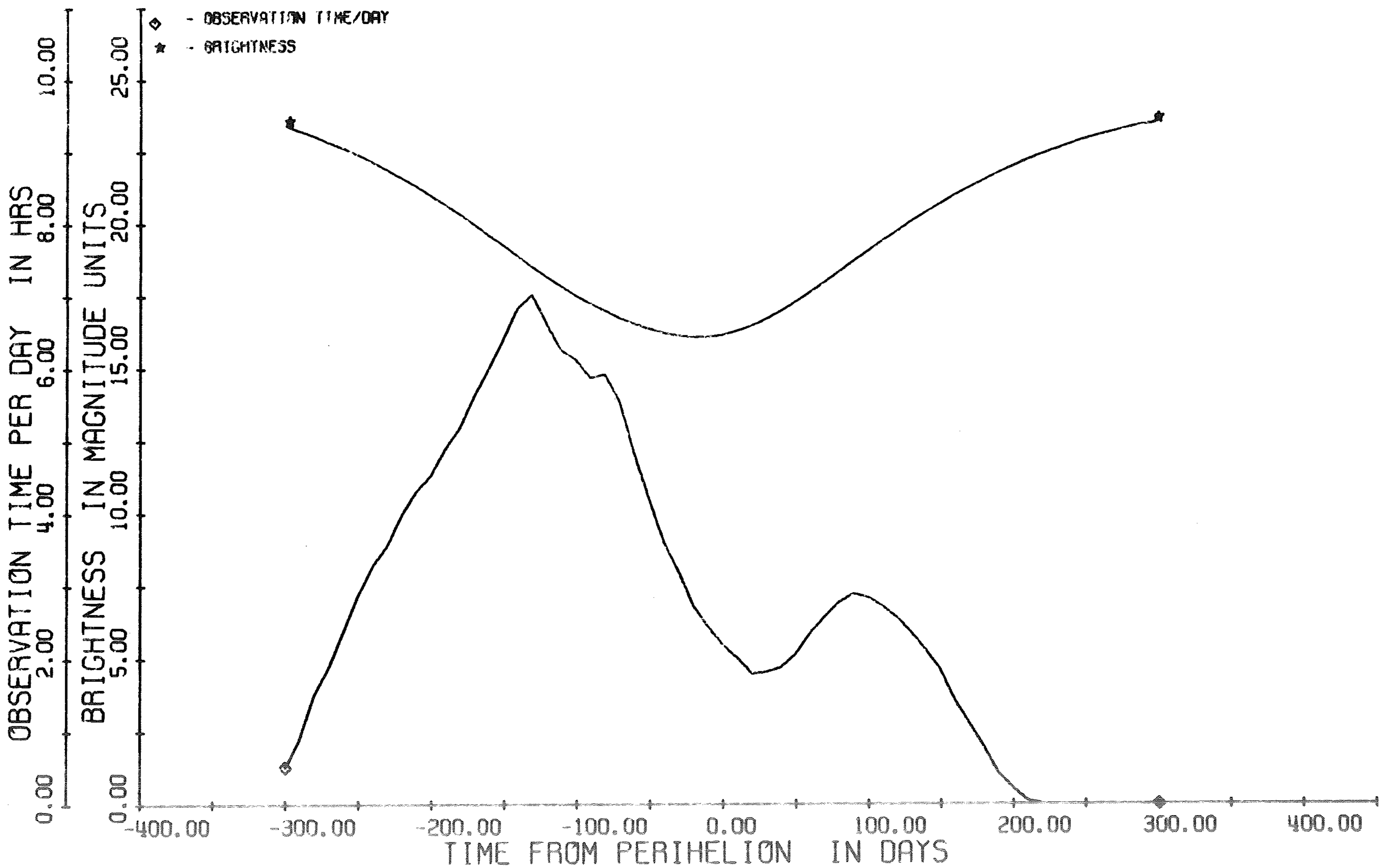


FIG A-2a. SIGHTING CONDITIONS FOR D'ARREST/82

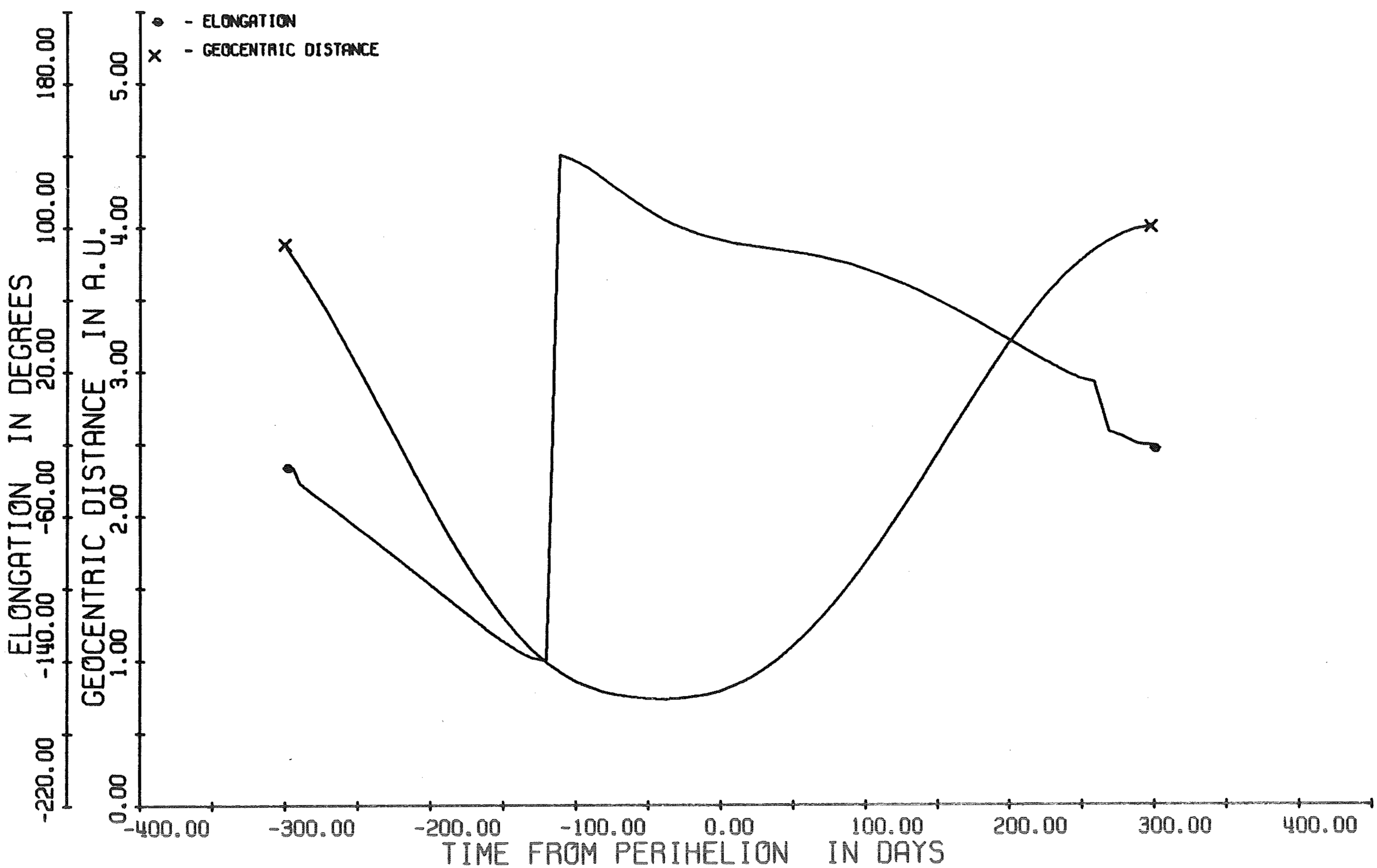
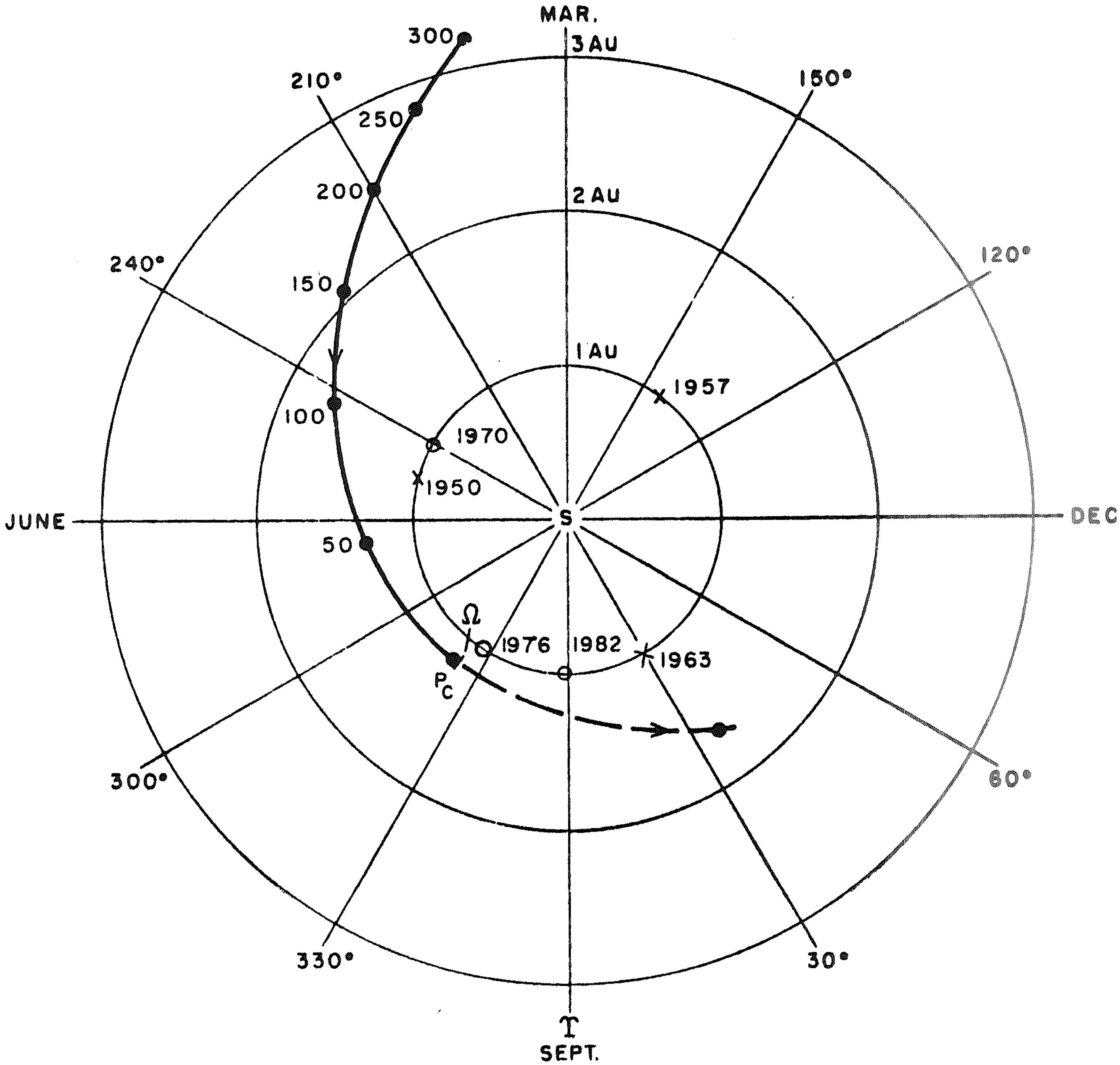


FIG A-2b. DISTANCE & ELONGATION FOR D'ARREST/82

D'ARREST



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-2c

TABLE A-2

OSCULATING ORBITAL ELEMENTS FOR COMET D'ARREST

EPOCH							
CALENDAR	JULIAN	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
10/18/63	2,438,320.5	3.544212	0.613599	18.0790	143.6059	174.5130	10/22/63
12/7/63	38,370.5	3.544684	0.613650	18.0787	143.6056	174.5145	6/25/70
12/26/65	39,120.5	3.537471	0.614365	18.1122	143.4777	174.4333	6/18/70
3/21/67	39,570.5	3.528678	0.617589	18.2389	143.3907	174.3400	6/10/70
8/18/67	39,720.5	3.520392	0.621721	18.3597	143.3878	174.3104	6/4/70
11/26/67	39,820.5	3.506065	0.628811	18.4737	143.4188	174.3912	5/28/70
3/5/68	39,920.5	3.463869	0.645872	18.2828	143.2957	175.2839	5/16/70
4/24/68	39,970.5	3.435021	0.653942	17.8128	142.9228	176.3351	5/13/70
8/2/68	40,070.5	3.407926	0.656966	17.1011	142.1604	177.7766	5/15/70
5/14/70	40,720.5	3.388418	0.654839	16.7439	141.4849	178.7666	5/18.4445/70
7/3/70	40,770.5	3.388658	0.654864	16.7438	141.4847	178.7672	8/12/76
6/2/72	41,470.5	3.388685	0.655270	16.7532	141.4566	178.7738	8/13/76
5/3/74	42,170.5	3.388018	0.655622	16.7634	141.4514	178.8074	8/13/76
7/11/76	42,970.5	3.385981	0.655347	16.7574	141.4297	178.8556	8/13.8250/76
8/30/76	43,020.5	3.386185	0.655370	16.7578	141.4287	178.8656	11/6/82
10/4/77	43,420.5	3.387681	0.656131	16.7871	141.2802	178.9701	11/8/82
12/28/78	43,870.5	3.367824	0.663351	17.3669	140.5491	179.1883	10/23/82
5/27/79	44,020.5	3.339819	0.673267	18.9501	139.8360	179.1077	9/23/82
9/4/79	44,120.5	3.365045	0.658585	20.7025	139.5285	177.8645	8/31/82
6/30/80	44,420.5	3.437620	0.627257	19.8596	139.2930	176.8240	9/15/82
8/4/81	44,820.5	3.447686	0.623069	19.6125	138.9825	176.8475	9/17/82
9/8/82	45,220.5	3.445350	0.622499	19.5922	138.8917	176.9296	9/17.7594/82
10/28/82	45,270.5	3.445504	0.622516	19.5921	138.8916	176.9309	2/8/89
9/27/84	45,970.5	3.446861	0.622845	19.5998	138.8662	176.9647	2/10/89
8/28/86	46,670.5	3.447107	0.622850	19.6033	138.8615	177.0094	2/11/89
12/25/88	47,520.5	3.446585	0.622337	19.5909	138.8334	177.0286	2/11.8674/89
2/13/89	47,570.5	3.446358	0.622312	19.5911	138.8331	177.0293	7/7/95

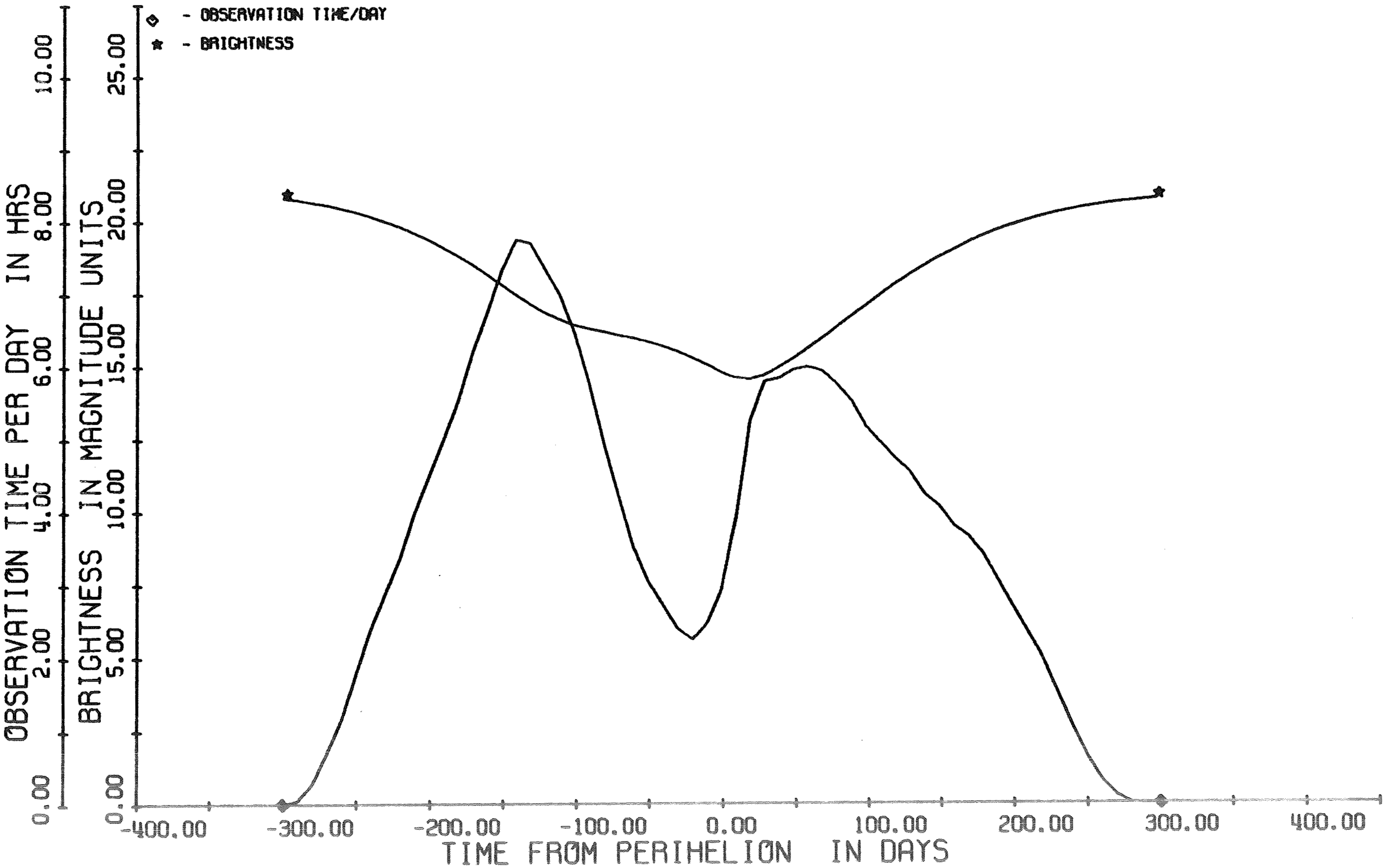


FIG A-3a. SIGHTING CONDITIONS FOR GRIGG-SKJELLERUP/82

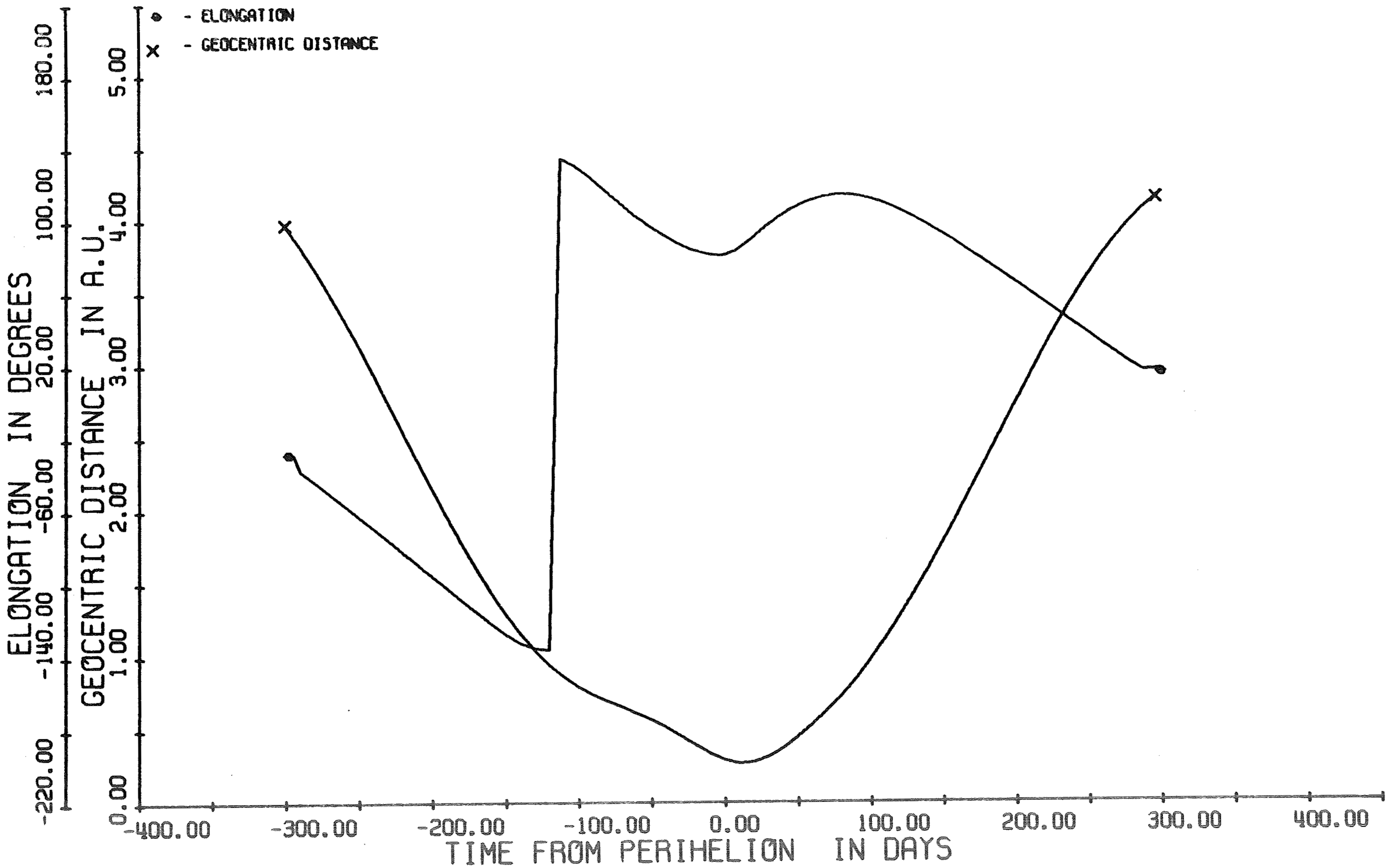
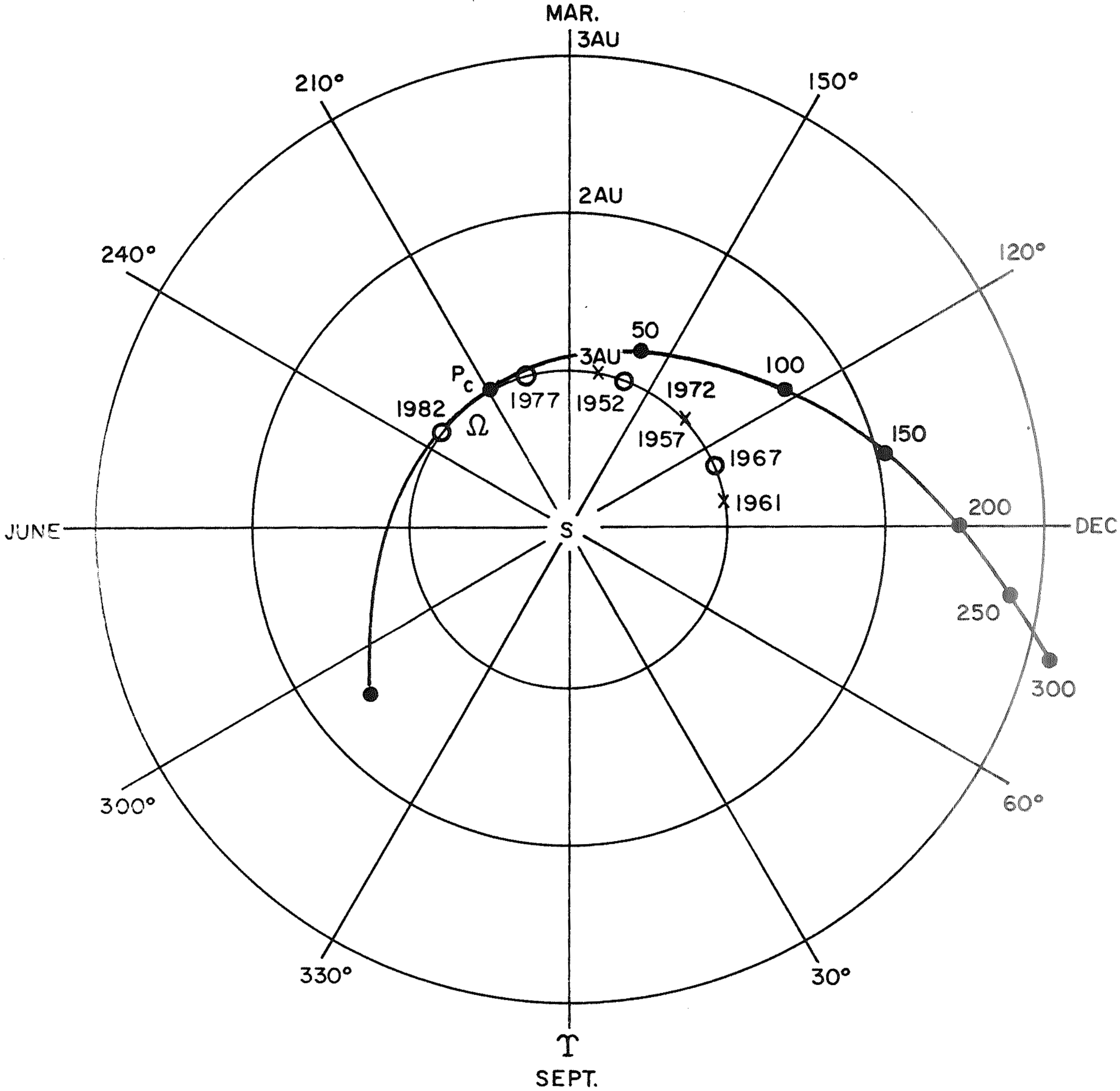


FIG A-3b. DISTANCE & ELONGATION FOR GRIGG-SKJELLERUP/82

GRIGG-SKJELLERUP



P$_c$ " PERIHELION OF COMET

O " POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X " PAST POSITIONS OF EARTH AT PERIHELION OF COMET

O " PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-3c

TABLE A-3

OSCULATING ORBITAL ELEMENTS FOR COMET GRIGG-SKJELLERUP

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
5/30/61	2,437,450.5	2.888	0.703	17.61	215.41	356.33	12/30/61
12/16/61	2,437,650.5	2.888	0.703	17.61	215.41	356.33	12/30/61
7/4/62	2,437,850.5	2.889	0.703	17.61	215.39	356.36	11/28/66
6/19/63	2,438,200.5	2.889	0.705	17.81	215.01	356.67	11/29/66
9/28/63	2,438,301.0	2.887	0.707	18.10	214.67	356.95	11/29/66
11/17/63	2,438,351.2	2.886	0.708	18.44	214.39	357.22	11/29/66
1/6/64	2,438,401.4	2.885	0.709	19.11	213.96	357.68	11/30/66
2/26/64	2,438,451.7	2.893	0.706	20.32	213.41	358.40	12/7/66
4/16/64	2,438,501.9	2.916	0.694	21.41	213.08	358.99	12/22/66
9/11/64	2,438,650.5	2.956	0.671	21.43	213.03	359.12	1/11/67
11/20/66	2,439,450.5	2.971	0.663	21.04	212.72	359.11	1/15/67
6/8/67	2,439,650.5	2.971	0.663	21.04	212.72	359.12	2/29/72
8/16/69	2,440,450.5	2.972	0.663	21.06	212.70	359.16	3/1/72
10/25/71	2,441,250.5	2.970	0.663	21.06	212.69	359.22	3/1/72
5/12/72	2,441,450.5	2.970	0.663	21.06	212.69	359.23	4/14/77
7/21/74	2,442,250.5	2.967	0.663	21.06	212.68	359.17	4/11/77
9/28/76	2,443,050.5	2.963	0.665	21.09	212.69	359.25	4/9/77
4/16/77	2,443,250.5	2.962	0.665	21.09	212.68	359.27	5/16/82
6/25/79	2,444,050.5	2.960	0.665	21.11	212.66	359.24	5/14/82
3/21/82	2,445,050.5	2.958	0.666	21.13	212.67	359.27	5/13/82
10/7/82	2,445,250.5	2.959	0.666	21.12	212.67	359.27	6/15/87
7/3/85	2,446,250.5	2.961	0.665	21.10	212.68	359.29	6/16/87

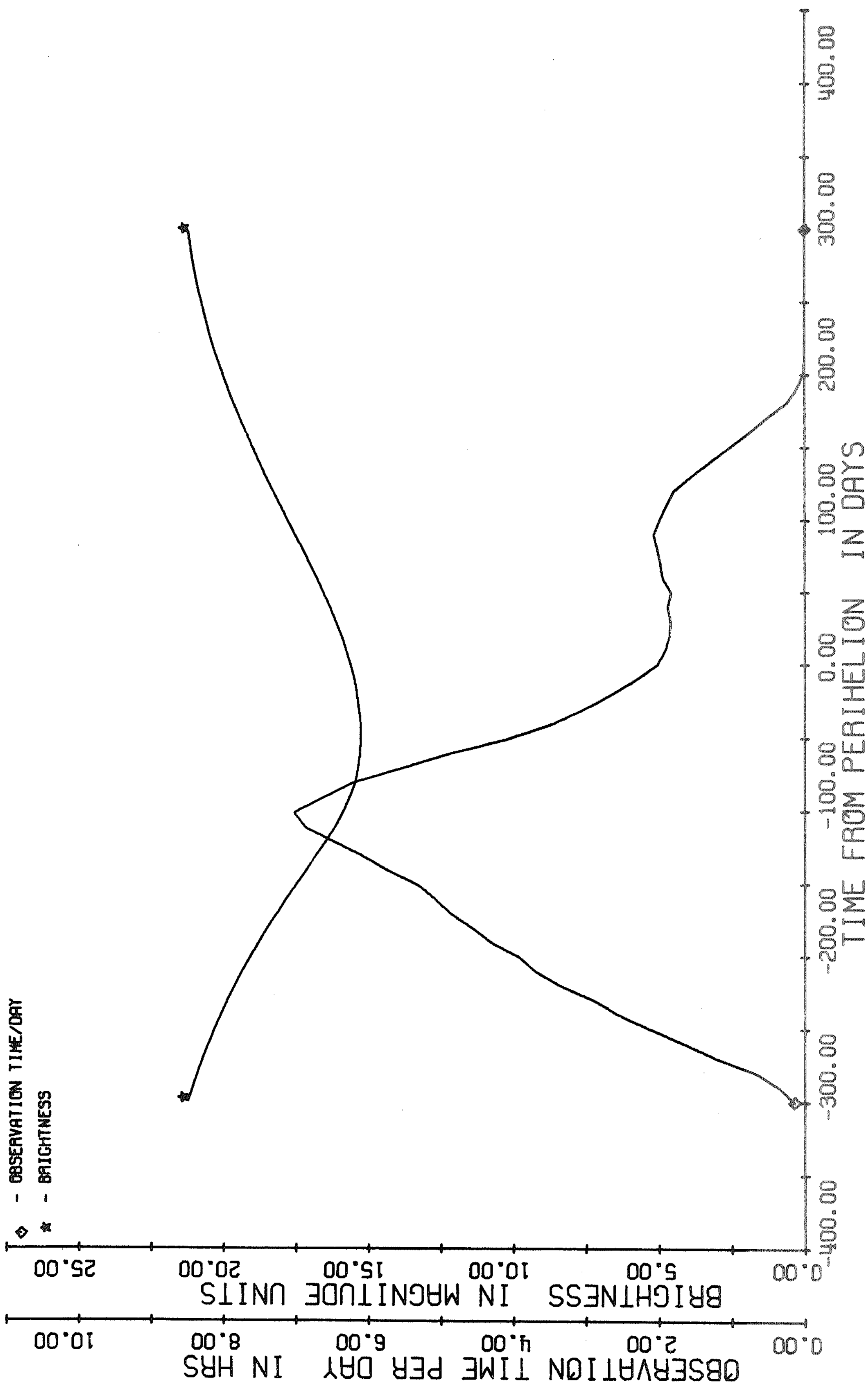


FIG A-4a. SIGHTING CONDITIONS FOR KOPFF/83

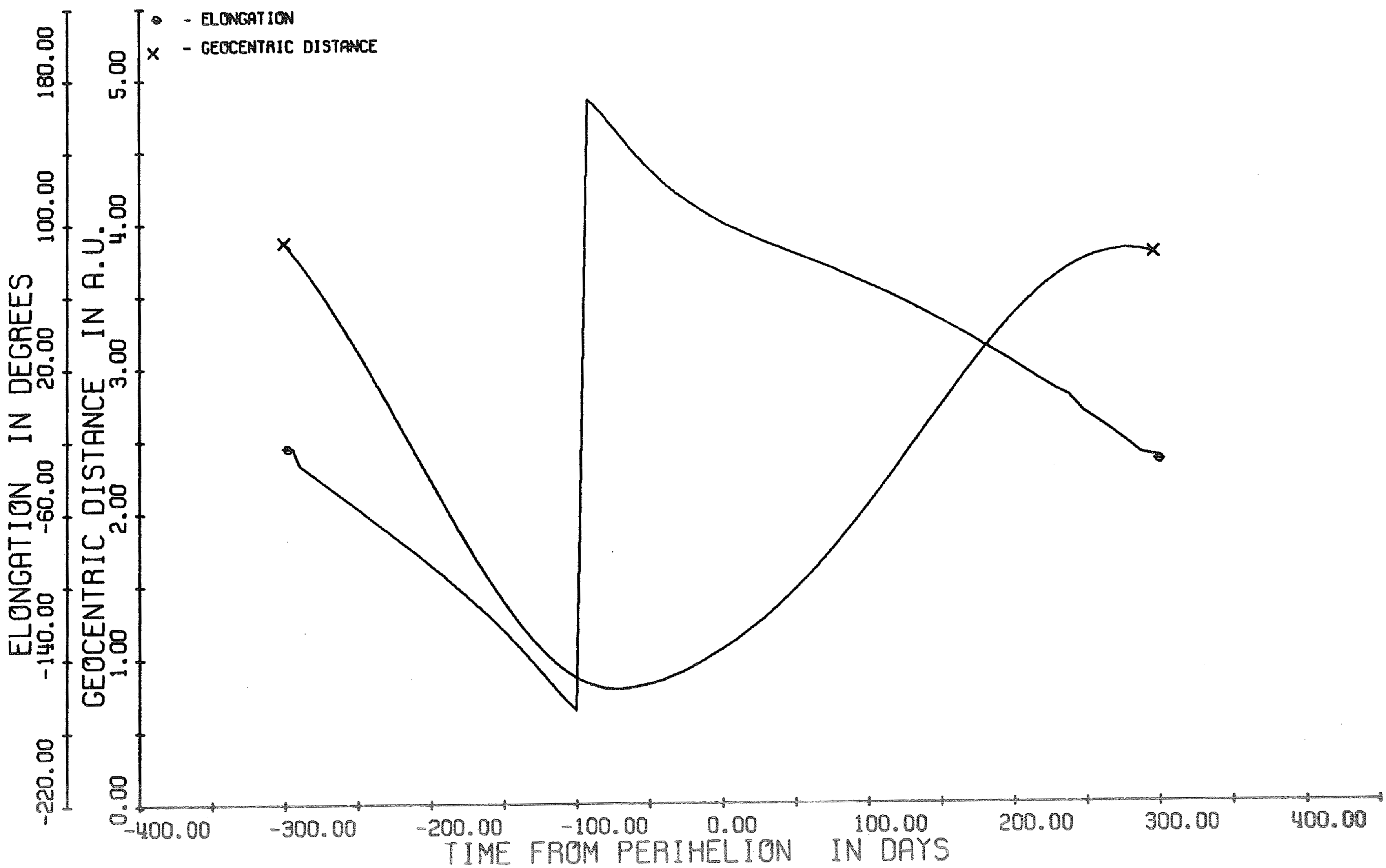
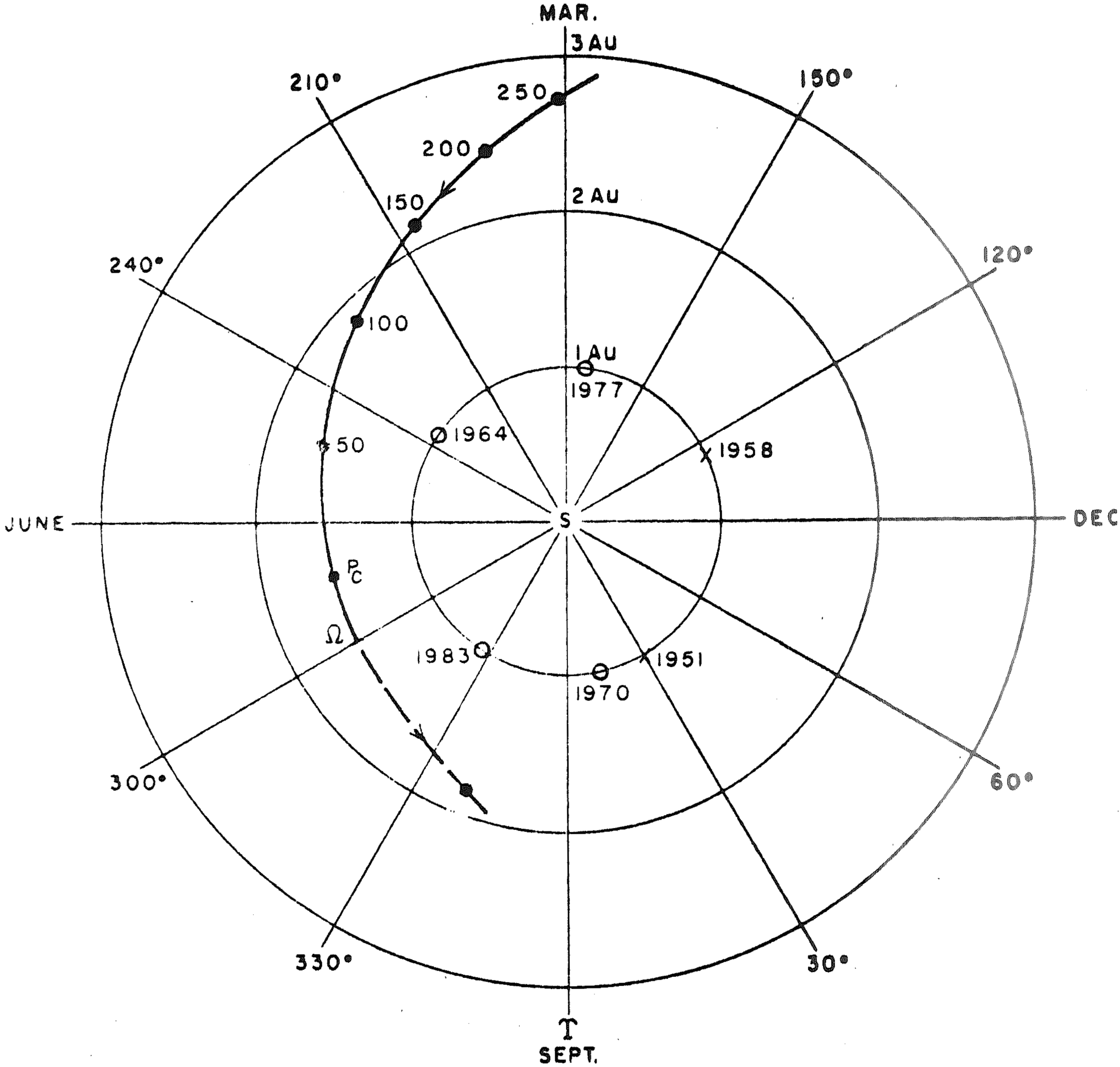


FIG A-4b. DISTANCE & ELONGATION FOR KOPFF/83

KOPFF



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-4c

TABLE A-4

OSCULATING ORBITAL ELEMENTS FOR COMET KOPFF

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
4/15/64	2,438,500.5	3.418	0.555	4.71	120.91	161.91	5/18/64
10/31/64	2,438,700.5	3.418	0.555	4.71	120.91	161.93	9/11/70
12/5/65	2,439,100.5	3.430	0.555	4.72	120.70	162.48	9/24/70
6/23/66	2,439,300.5	3.438	0.552	4.73	120.54	162.87	10/1/70
4/23/70	2,440,700.5	3.456	0.547	4.73	120.45	162.72	10/6/70
11/9/70	2,440,900.5	3.454	0.547	4.73	120.44	162.73	3/8/77
2/21/74	2,442,100.5	3.459	0.547	4.73	120.40	162.89	3/13/77
11/17/76	2,443,100.5	3.460	0.546	4.73	120.39	162.87	3/14/77
6/5/77	2,443,300.5	3.460	0.546	4.73	120.39	162.87	8/20/83
9/17/80	2,444,500.5	3.460	0.545	4.73	120.38	162.86	8/19/83
6/14/83	2,445,500.5	3.463	0.545	4.73	120.37	162.78	8/18/83
12/31/83	2,445,700.5	3.462	0.545	4.73	120.36	162.77	1/26/90
8/22/85	2,446,300.5	3.465	0.545	4.73	120.36	162.85	1/29/90

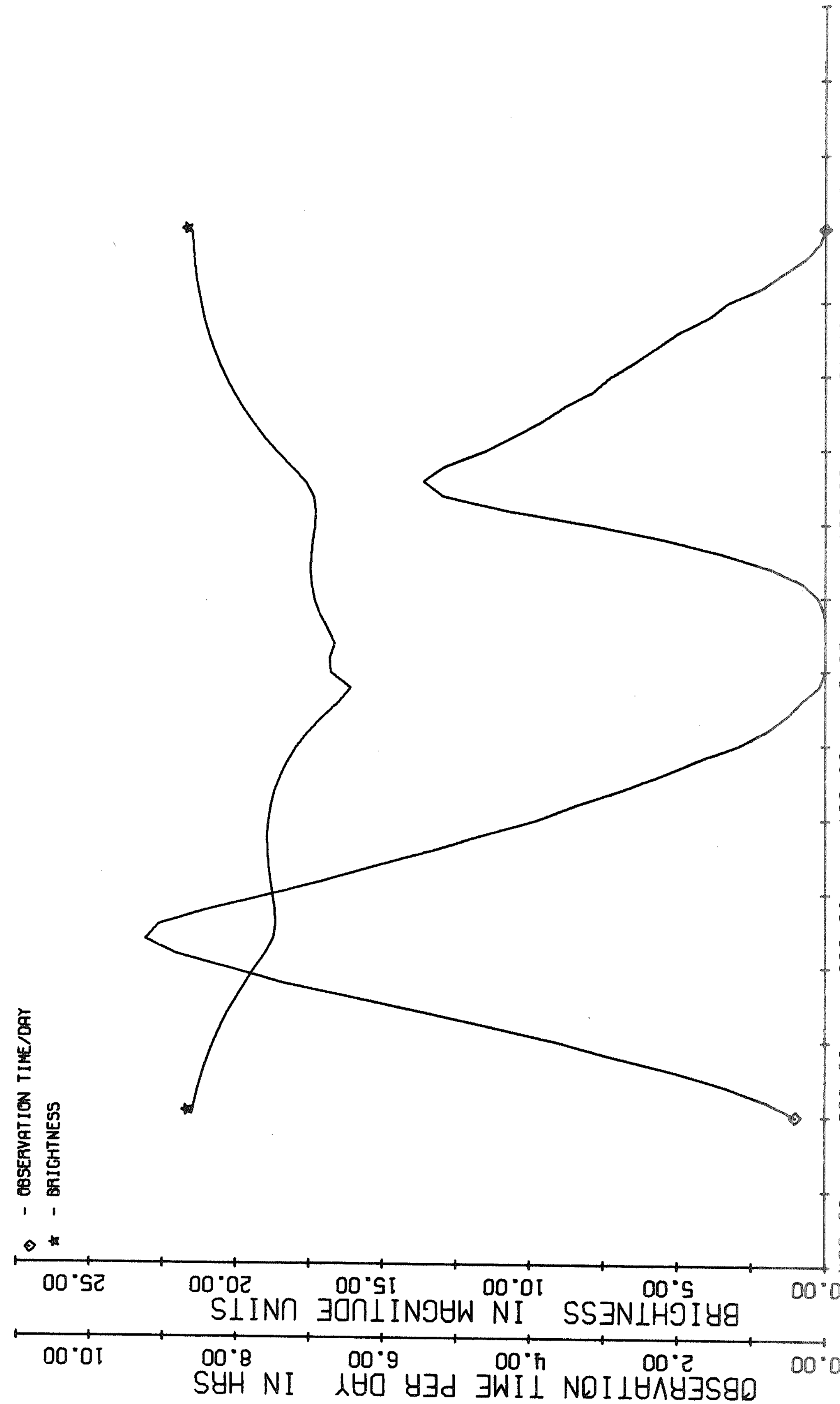


FIG A-5a. SIGHTING CONDITIONS FOR ENCKE/84

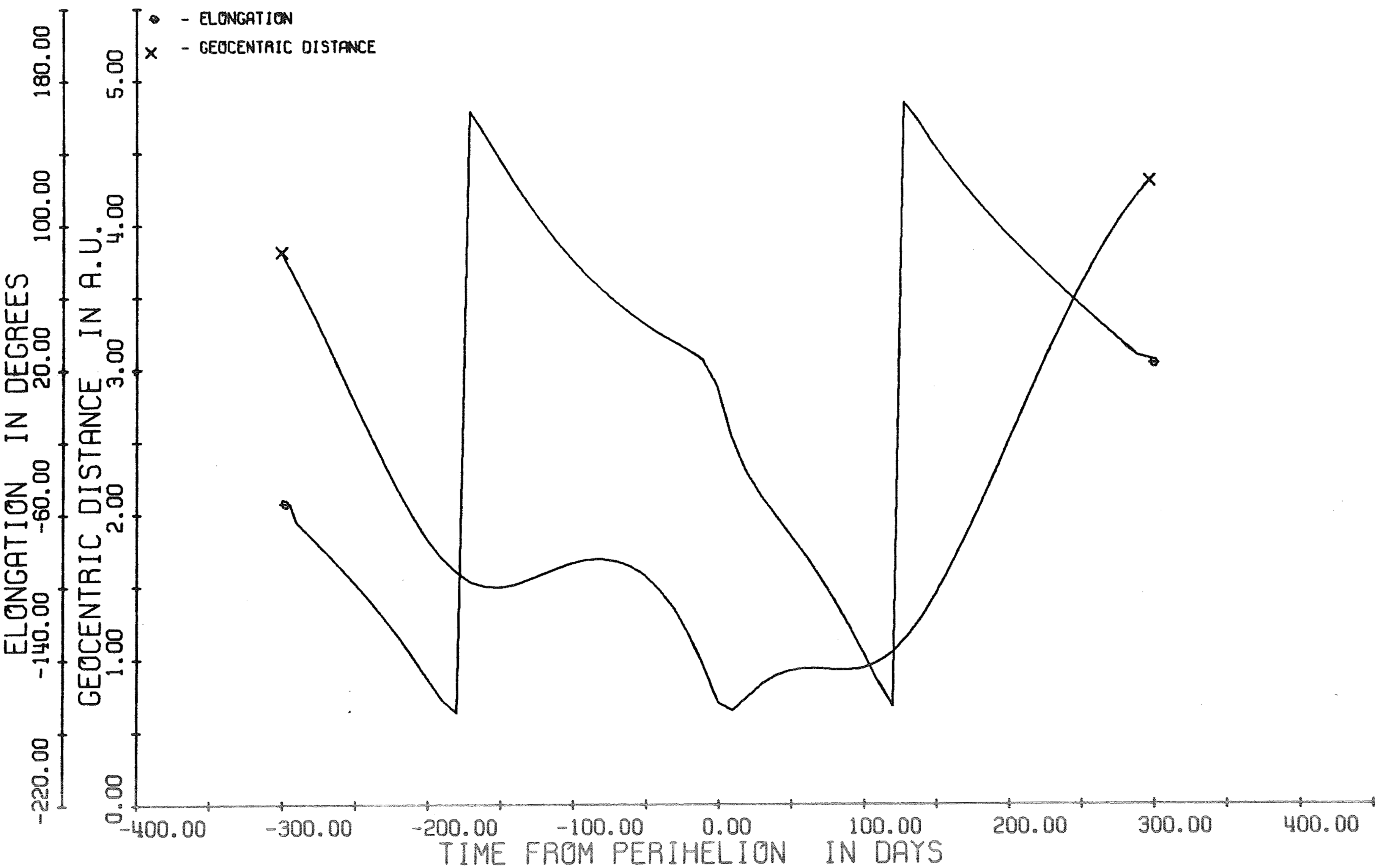
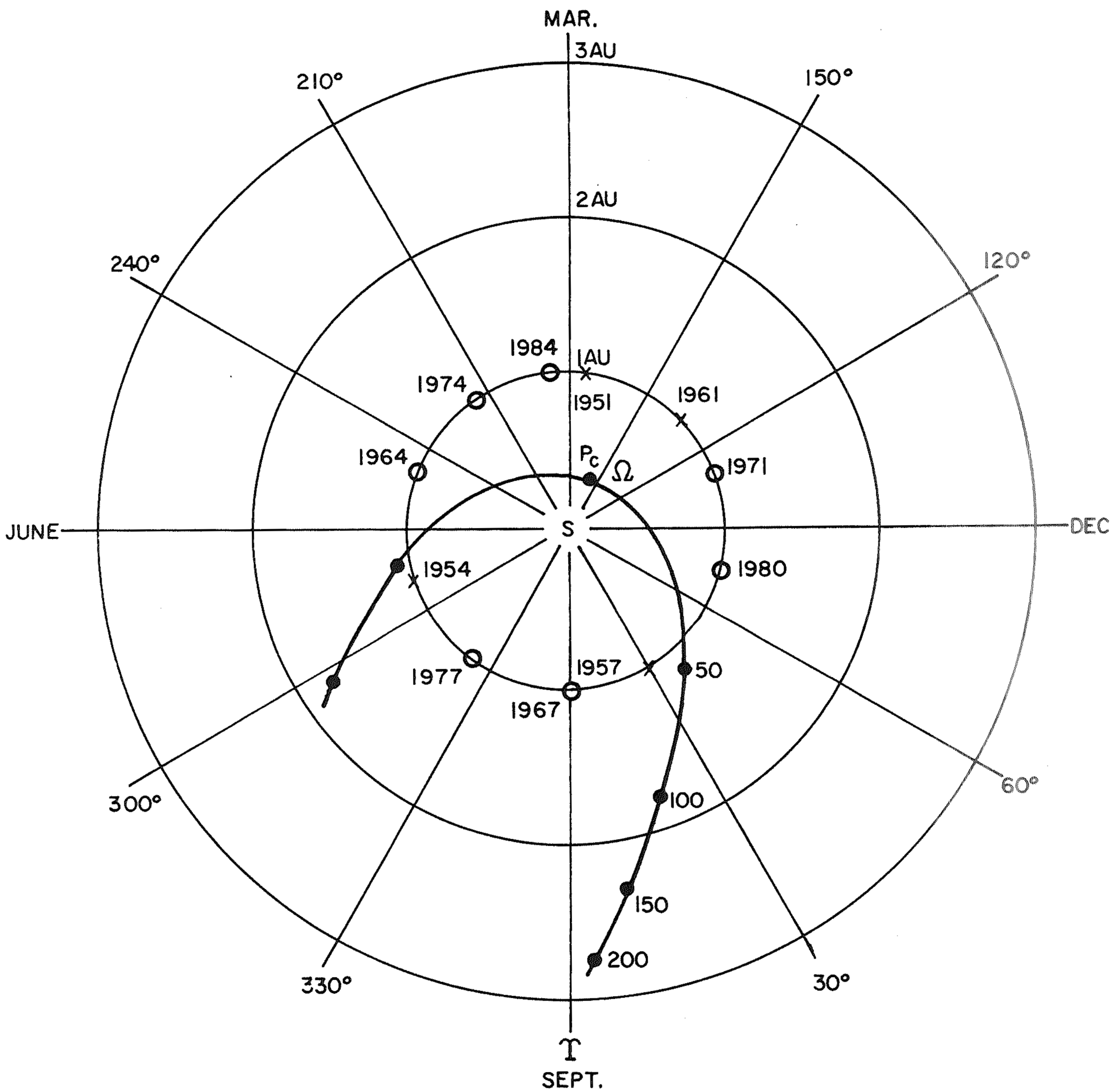


FIG A-5b. DISTANCE & ELONGATION FOR ENCKE/84

ENCKE



P_c " PERIHELION OF COMET

● " POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

x " PAST POSITIONS OF EARTH AT PERIHELION OF COMET

o " PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-5c

TABLE A-5

OSCULATING ORBITAL ELEMENTS FOR COMET ENCKE

Epoch: Calendar	Epoch: Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
6/4/64	2,438,550.5	2.217	0.847	11.97	334.23	185.91	9/22/67
1/24/66	2,439,150.5	2.217	0.847	11.97	334.23	185.91	9/21/67
9/16/67	2,439,750.5	2.217	0.847	11.99	334.23	185.92	9/21/67
4/3/68	2,439,950.5	2.217	0.847	11.99	334.23	185.92	1/9/71
11/24/69	2,440,550.5	2.217	0.847	11.98	334.23	185.94	1/9/71
12/29/70	2,440,950.5	2.217	0.847	11.97	334.21	185.95	1/9/71
7/17/71	2,441,150.5	2.217	0.847	11.97	334.21	185.95	4/29/74
3/8/73	2,441,750.5	2.217	0.847	11.98	334.21	185.93	4/28/74
4/12/74	2,442,150.5	2.217	0.847	11.98	334.22	185.93	4/28/74
10/29/74	2,442,350.5	2.217	0.847	11.98	334.22	185.94	8/16/77
6/20/76	2,442,950.5	2.218	0.847	11.94	334.22	185.96	8/16/77
7/25/77	2,443,350.5	2.219	0.847	11.94	334.21	185.96	8/16/77
2/10/78	2,443,550.5	2.219	0.847	11.94	334.20	185.96	12/6/80
10/3/79	2,444,150.5	2.219	0.847	11.95	334.20	185.96	12/6/80
11/6/80	2,444,550.5	2.218	0.847	11.95	334.19	185.98	12/6/80
5/25/81	2,444,750.5	2.218	0.847	11.94	334.19	185.99	3/27/84
1/15/83	2,445,350.5	2.219	0.846	11.93	334.19	186.00	3/27/84
2/19/84	2,445,750.5	2.219	0.846	11.93	334.18	186.00	3/27/84
9/6/84	2,445,950.5	2.219	0.846	11.93	334.17	186.00	7/18/87
11/30/85	2,446,400.5	2.217	0.848	11.98	334.15	185.97	7/17/87

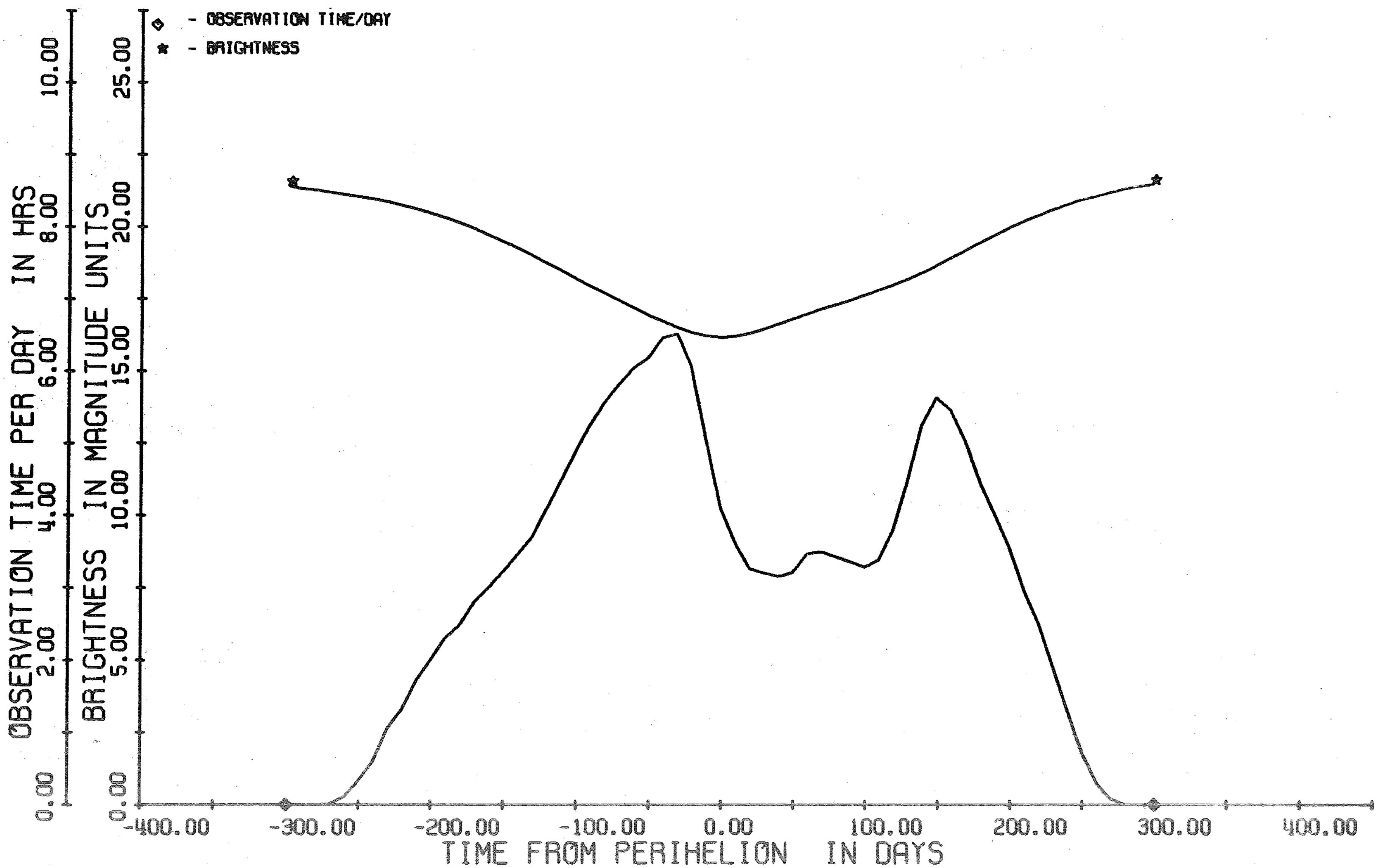


FIG A-6a. SIGHTING CONDITIONS FOR GIACOBINI-ZINNER/85

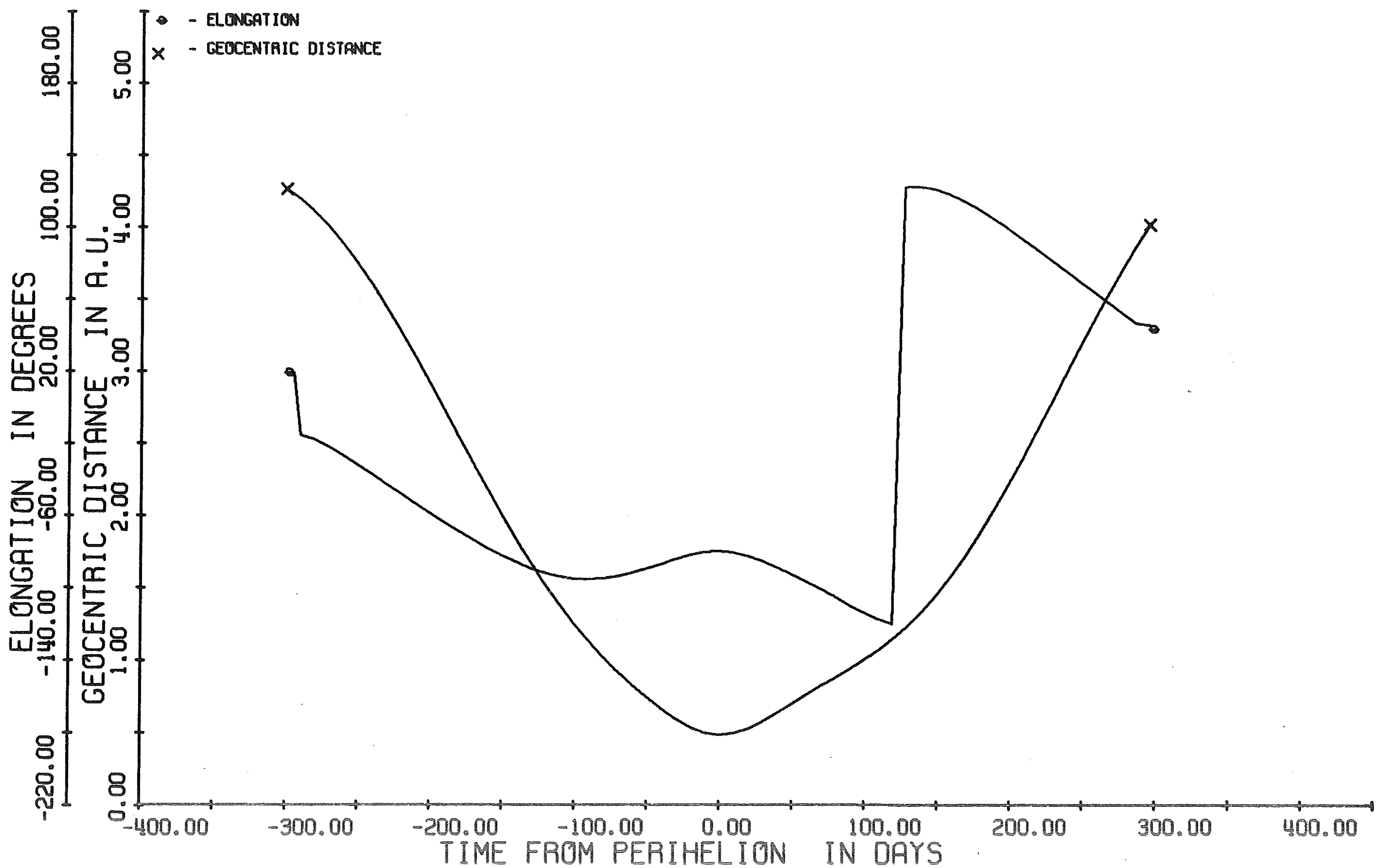
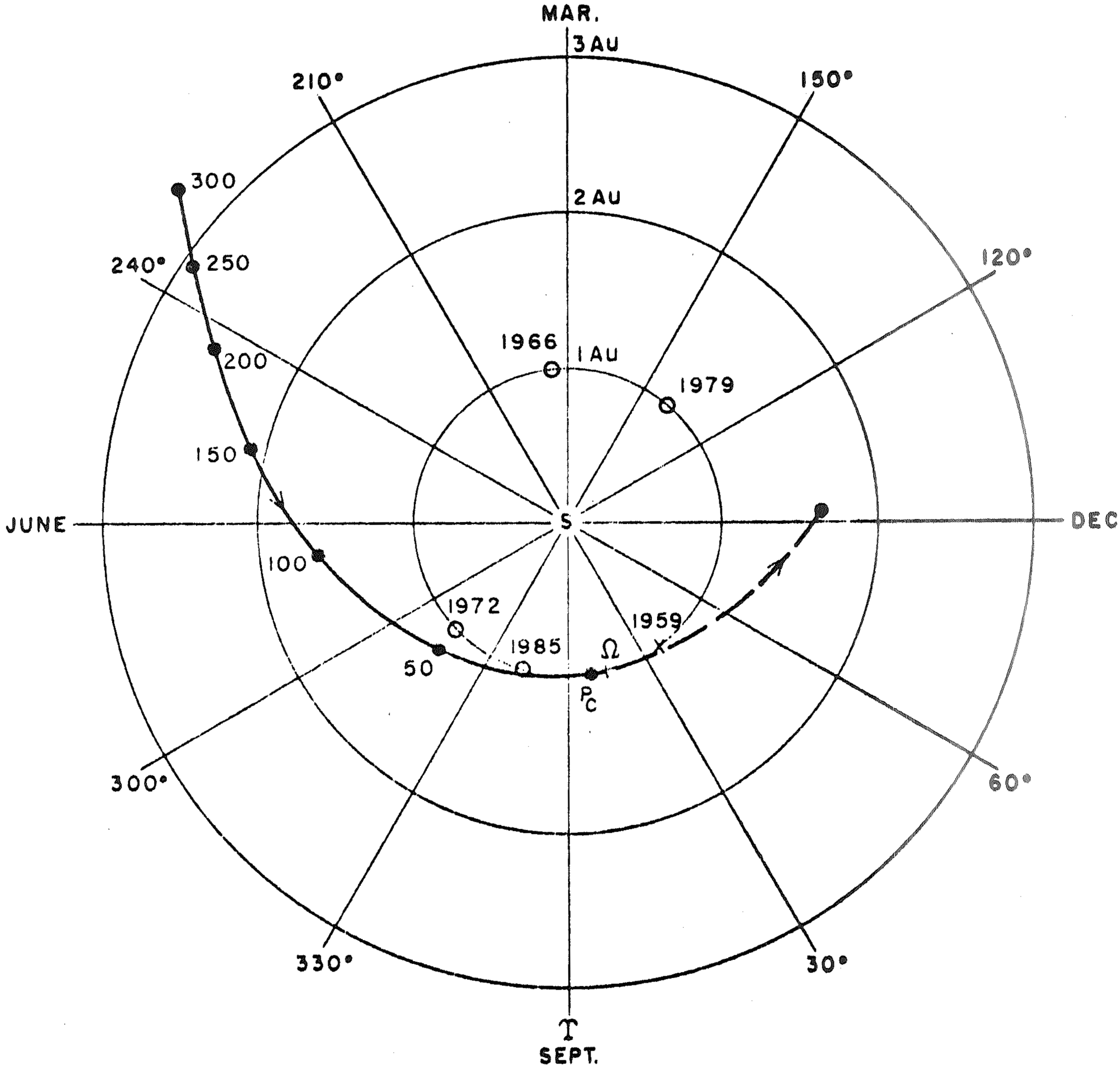


FIG A-6b. DISTANCE & ELONGATION FOR GIACOBINI-ZINNER/85

GIACOBINI-ZINNER



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-6c

TABLE A-6

OSCULATING ORBITAL ELEMENTS FOR COMET GIACOBINI-ZINNER

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
10/8/59	2,436,850.5	3.453	0.729	30.91	196.03	172.84	10/26/59
4/25/60	2,437,050.5	3.453	0.729	30.91	196.03	172.84	3/27/66
1/20/63	2,438,050.5	3.452	0.730	30.95	195.98	172.87	3/27/66
10/16/65	2,439,050.5	3.450	0.729	30.95	195.97	172.92	3/27/66
5/4/66	2,439,250.5	3.449	0.729	30.95	195.96	172.92	8/22/72
8/16/69	2,440,450.5	3.441	0.731	32.31	195.39	172.83	8/3/72
10/31/69	2,440,526.5	3.454	0.727	32.54	195.37	172.47	7/31/72
5/12/72	2,441,450.5	3.489	0.715	31.71	195.13	171.88	8/3/72
11/28/72	2,441,650.5	3.489	0.715	31.71	195.13	171.89	2/9/79
3/12/76	2,442,850.5	3.491	0.715	31.74	195.09	171.95	2/11/79
12/7/78	2,443,850.5	3.491	0.714	31.70	195.07	171.95	2/11/79
6/25/79	2,444,050.5	3.491	0.714	31.70	195.06	171.96	8/21/85
7/29/80	2,444,450.5	3.497	0.714	31.78	194.91	172.20	8/27/85
2/14/81	2,444,650.5	3.503	0.712	31.921	194.75	172.47	9/1/85
9/2/81	2,444,850.5	3.507	0.710	31.980	194.71	172.58	9/4/85
7/3/85	2,446,250.5	3.517	0.707	31.888	194.70	172.47	9/4/85

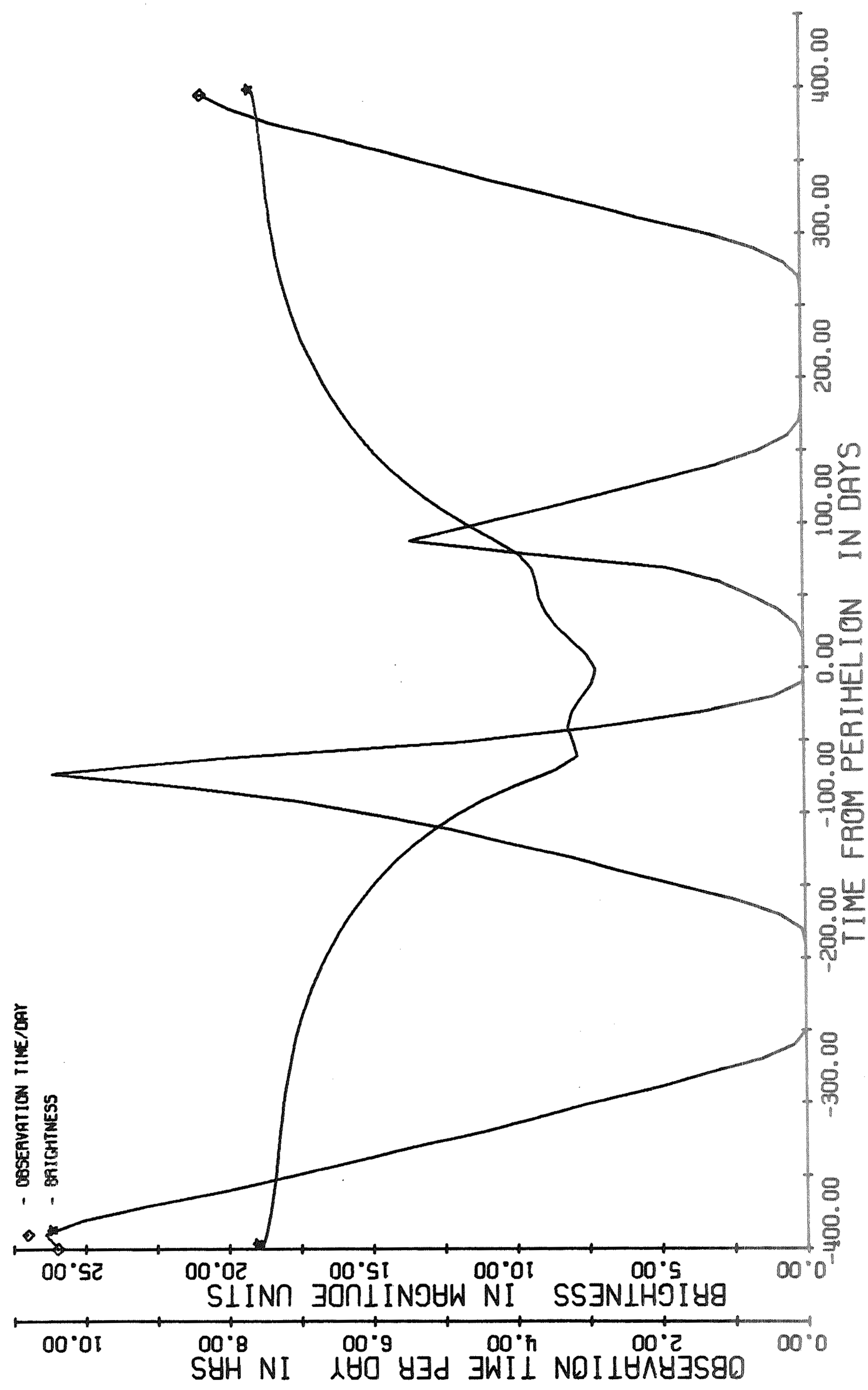


FIG A-7a. SIGHTING CONDITIONS FOR HALLEY/86

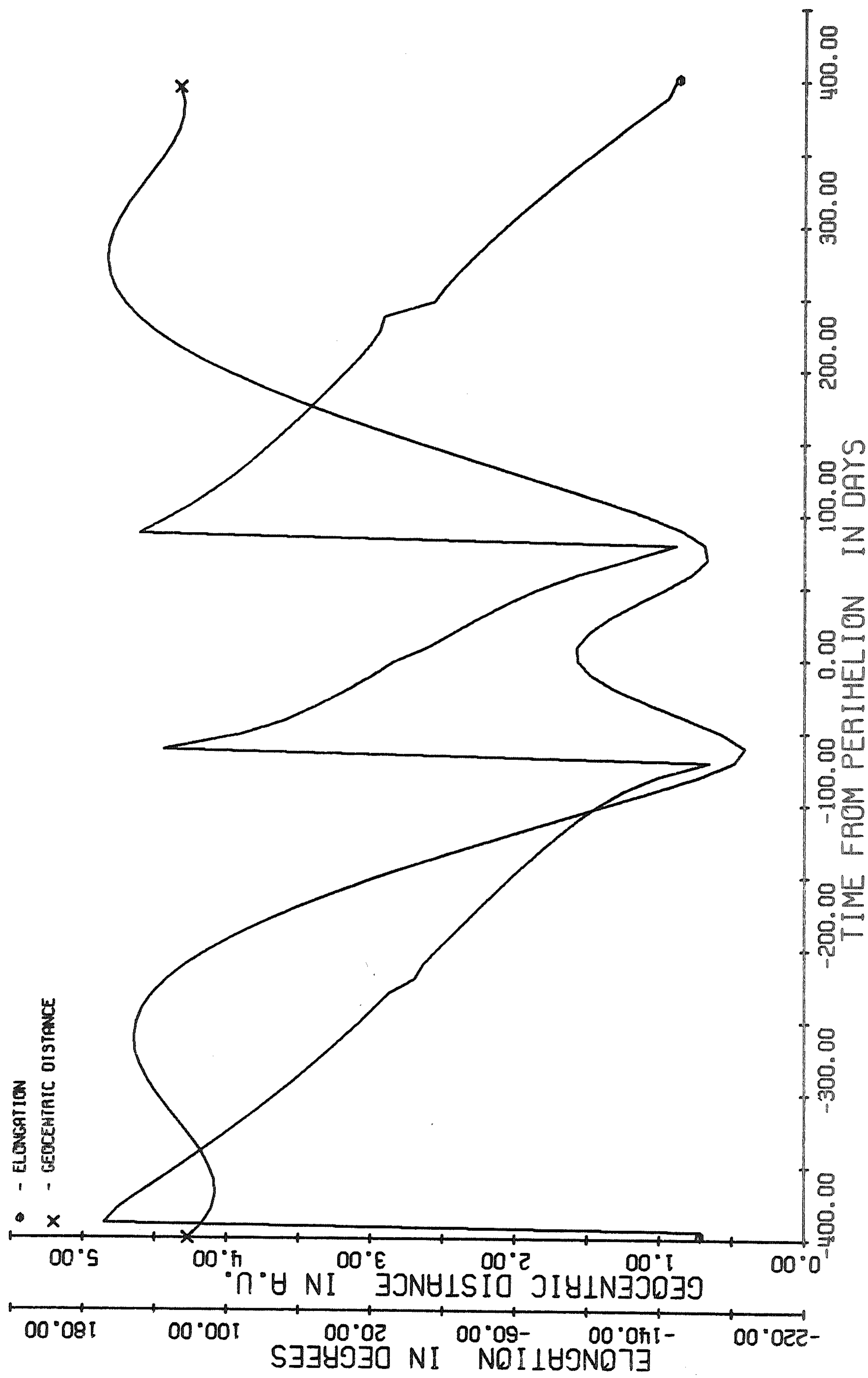
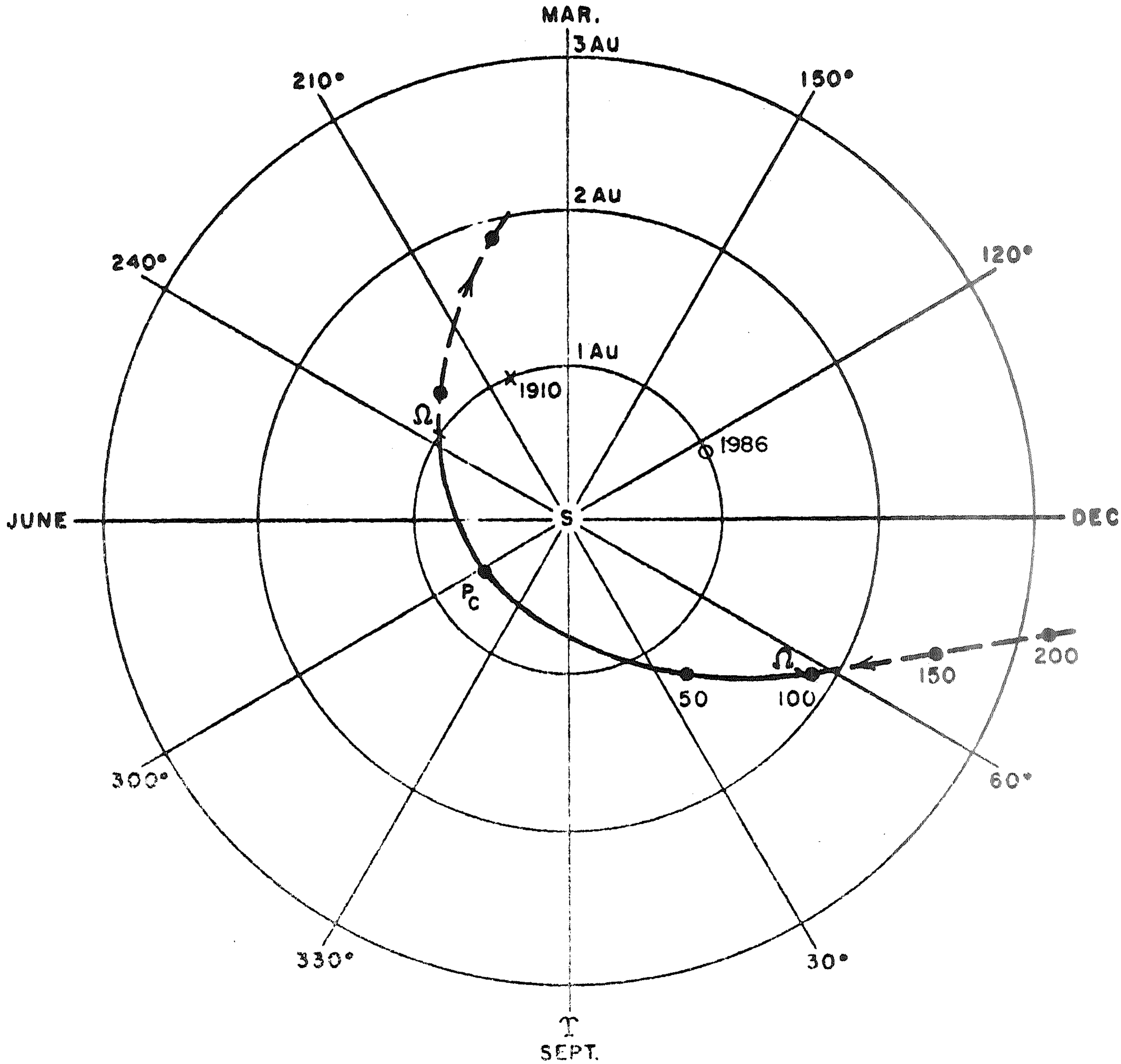


FIG A-7b. DISTANCE & ELONGATION FOR HALLEY/86

HALLEY



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-7c

TABLE A-7

OSCULATING ORBITAL ELEMENTS FOR COMET HALLEY

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
4/19/10*	2,418,781.5	17.947	0.967	162.21	57.84	111.72	5/1/86
1/13/13	2,419,781.5	17.911	0.967	162.22	57.90	111.78	2/5/86
10/10/15	2,420,781.5	17.998	0.967	162.22	58.27	112.19	8/29/86
7/6/18	2,421,781.5	17.970	0.968	162.21	58.43	112.19	6/27/86
4/1/21	2,422,781.5	17.888	0.968	162.24	57.83	111.54	12/11/85
12/27/23	2,423,781.5	17.877	0.967	162.27	57.41	111.25	11/11/85
9/22/26	2,424,781.5	17.923	0.967	162.23	57.95	111.87	3/2/86
6/18/29	2,425,781.5	17.933	0.967	162.17	58.64	112.46	4/6/86
3/14/32	2,426,781.5	17.901	0.968	162.22	58.14	111.90	1/12/86
12/9/34	2,427,781.5	17.894	0.967	162.28	57.45	111.27	12/13/85
9/4/37	2,428,781.5	17.915	0.966	162.24	57.82	111.70	2/8/86
5/31/40	2,429,781.5	17.922	0.967	162.13	58.90	112.73	3/22/86
2/25/43	2,430,781.5	17.904	0.968	162.15	58.76	112.54	2/1/86
11/21/45	2,431,781.5	17.902	0.968	162.26	57.74	111.54	12/21/85
5/14/51	2,433,781.5	17.908	0.967	162.18	58.37	112.18	2/7/86
2/7/54	2,434,781.5	17.900	0.968	162.14	58.67	112.48	1/22/86
11/3/56	2,435,781.5	17.913	0.968	162.27	57.78	111.60	12/27/85

* Porter (1961)

TABLE A-7 (Continued)

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
7/31/59	2,436,781.5	17.925	0.967	162.34	57.28	111.06	1/1/86
4/26/62	2,437,781.5	17.906	0.966	162.23	57.97	111.73	1/24/86
1/20/65	2,438,781.5	17.884	0.967	162.11	58.75	112.58	1/24/86
10/17/67	2,439,781.5	17.911	0.968	162.18	58.34	112.19	1/9/86
7/13/70	2,440,781.5	17.941	0.967	162.28	57.74	111.53	1/6/86
4/8/73	2,441,781.5	17.916	0.967	162.25	57.93	111.66	1/13/86
1/3/76	2,442,781.5	17.875	0.967	162.13	58.53	112.35	1/14/86
9/29/78	2,443,781.5	17.937	0.968	162.15	58.43	112.32	1/9/86
6/25/81	2,444,781.5	18.035	0.968	162.24	58.06	111.85	1/7/86
3/21/84	2,445,781.5	18.003	0.967	162.26	58.00	111.69	1/8/86
11/11/85	2,446,381.5	17.929	0.967	162.25	58.02	111.74	1/8/86*
2/19/86	2,446,481.5	17.930	0.967	162.25	58.02	111.74	12/12/2061
12/16/86	2,446,781.5	17.974	0.967	162.25	58.05	111.77	3/24/2062
7/4/87	2,446,981.5	17.994	0.967	162.25	58.08	111.79	5/9/2062
1/20/88	2,447,181.5	18.004	0.967	162.25	58.11	111.81	5/31/2062
8/7/88	2,447,381.5	18.000	0.968	162.25	58.13	111.80	5/23/2062
2/23/89	2,447,581.5	17.987	0.968	162.25	58.13	111.77	4/22/2062
9/11/89	2,447,781.5	17.967	0.968	162.25	58.11	111.73	3/8/2062
3/30/90	2,447,981.5	17.942	0.968	162.25	58.07	111.66	1/9/2062
10/16/90	2,448,181.5	17.918	0.968	162.25	58.02	111.59	11/13/2061
5/4/91	2,448,381.5	17.892	0.968	162.26	57.95	111.51	9/14/2061
11/20/91	2,448,581.5	17.871	0.968	162.26	57.88	111.44	7/28/2061

* The nuclear-electric flight mode results were computed for a predicted perihelion date of 1/18/86. An updated and improved prediction of perihelion is 2/4/86 (gravitational theory alone) and 2/9/86 (non-gravitational forces included) - Michielsen, 1968.

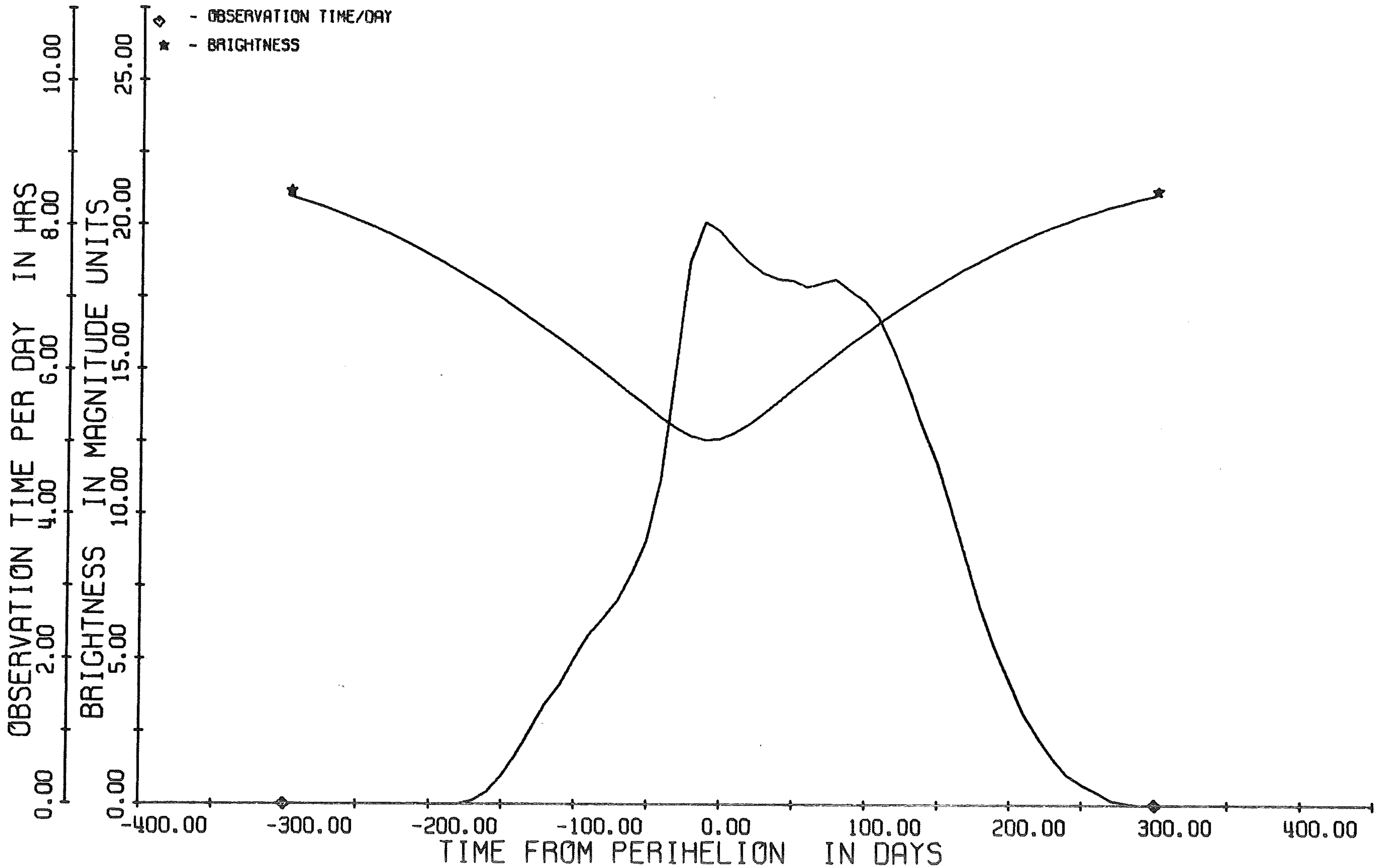


FIG A-8a. SIGHTING CONDITIONS FOR BORRELLEY/87

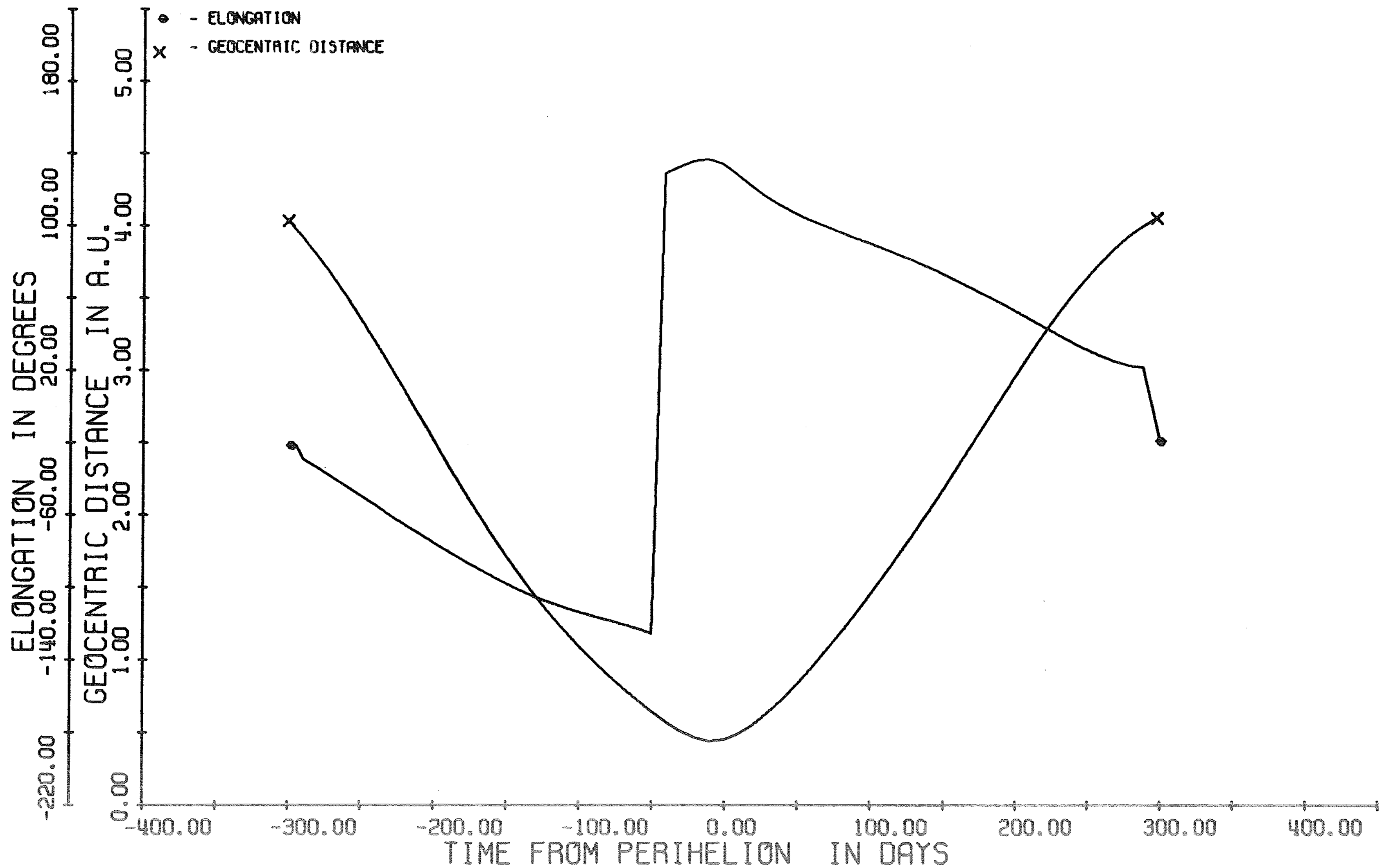
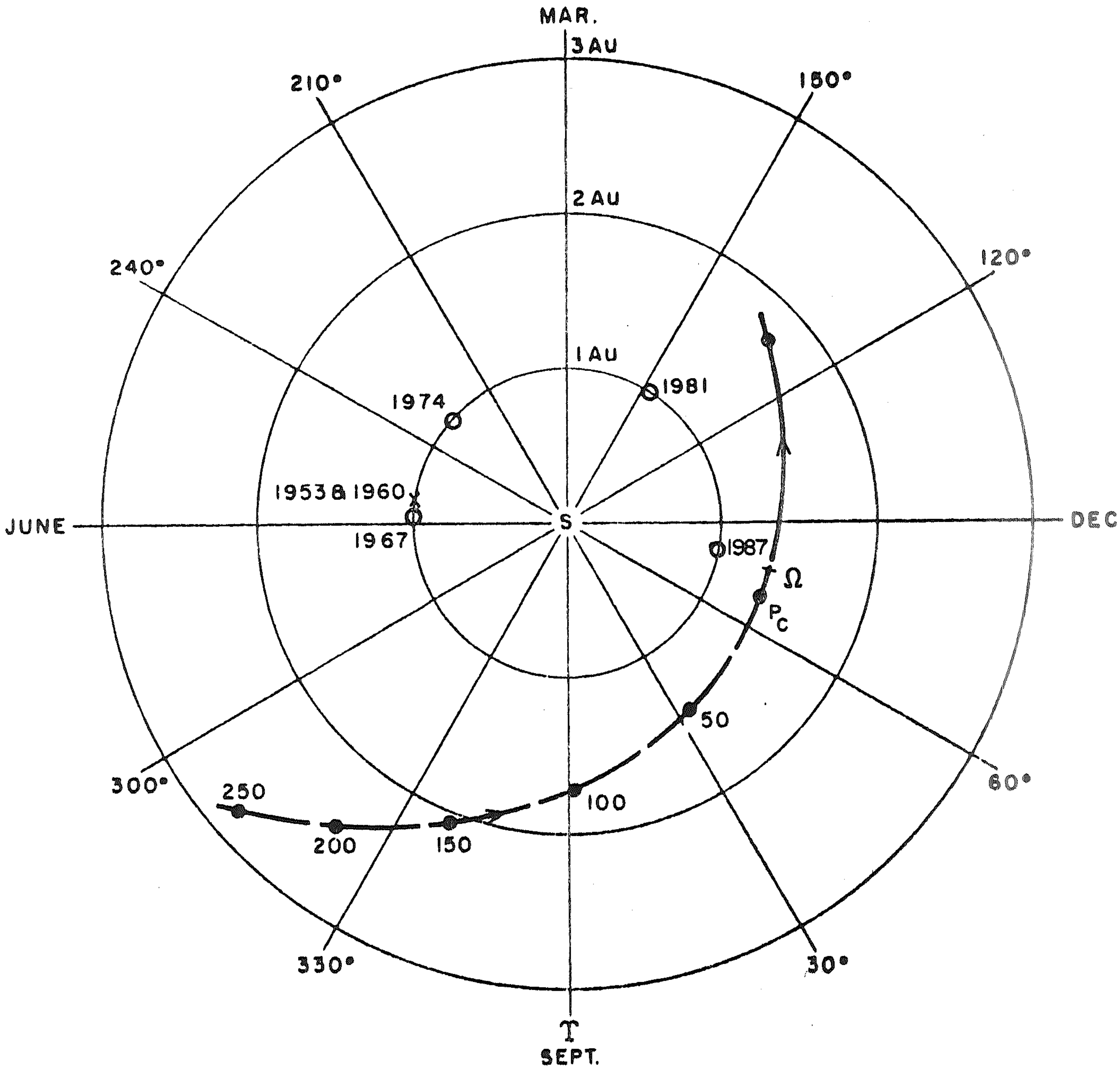


FIG A-8b. DISTANCE & ELONGATION FOR BORRELLEY/87

BORRELLY



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-8c

TABLE A-8

OSCULATING ORBITAL ELEMENTS FOR COMET BORRELLY

Epoch Calendar	Epoch Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
6/15/60	2,437,100.5	3.667	0.604	31.09	76.23	350.75	6/20/67
9/27/63	2,438,300.5	3.662	0.605	31.12	76.19	350.70	6/17/67
1/9/67	2,439,500.5	3.658	0.605	31.14	76.18	350.80	6/17/67
7/28/67	2,439,700.5	3.658	0.605	31.14	76.18	350.80	6/15/74
5/28/71	2,441,100.5	3.644	0.609	31.42	75.99	350.68	6/1/74
8/5/73	2,441,900.5	3.579	0.633	30.22	75.18	352.42	5/11/74
9/9/74	2,442,300.5	3.577	0.633	30.22	75.15	352.48	2/14/81
12/22/77	2,443,500.5	3.579	0.633	30.23	75.12	352.56	2/17/81
3/1/80	2,444,300.5	3.579	0.633	30.20	75.10	352.57	2/18/81
4/5/81	2,444,700.5	3.579	0.632	30.20	75.09	352.57	11/27/87
6/14/83	2,445,500.5	3.597	0.629	30.39	74.79	353.24	12/13/87
8/22/85	2,446,300.5	3.606	0.625	30.34	74.79	353.19	12/16/87

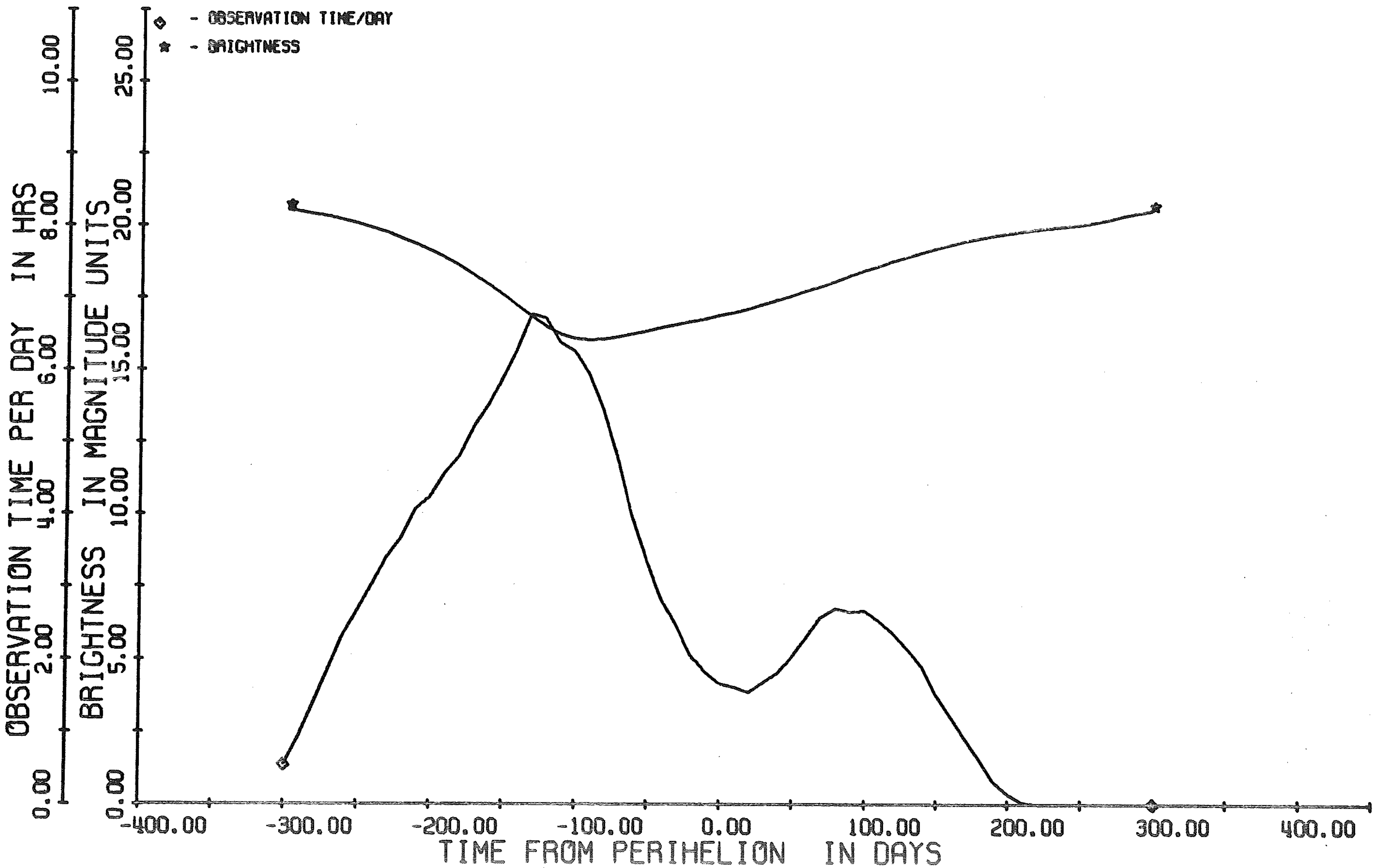


FIG A-9a. SIGHTING CONDITIONS FOR TEMPLE-2/88

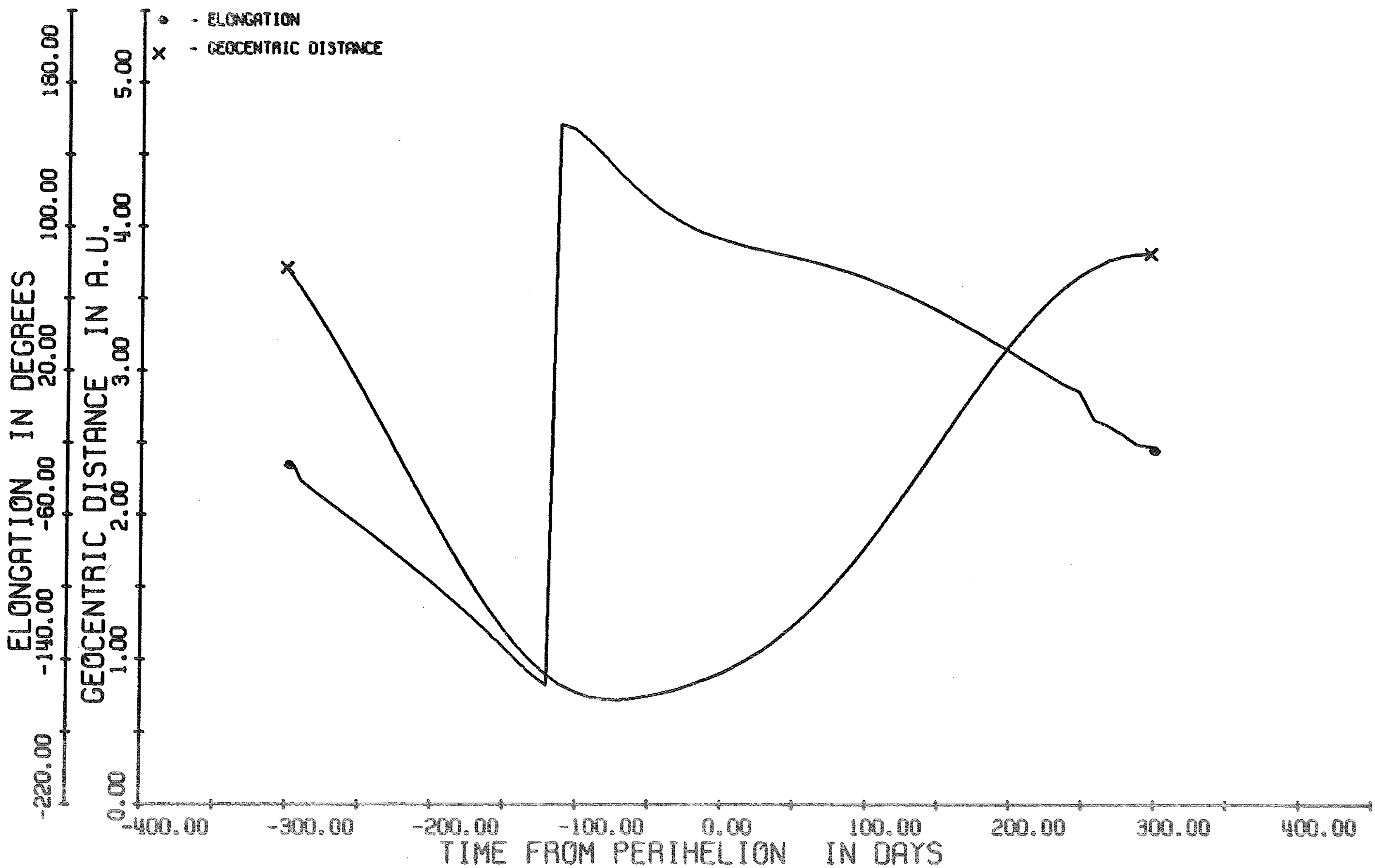
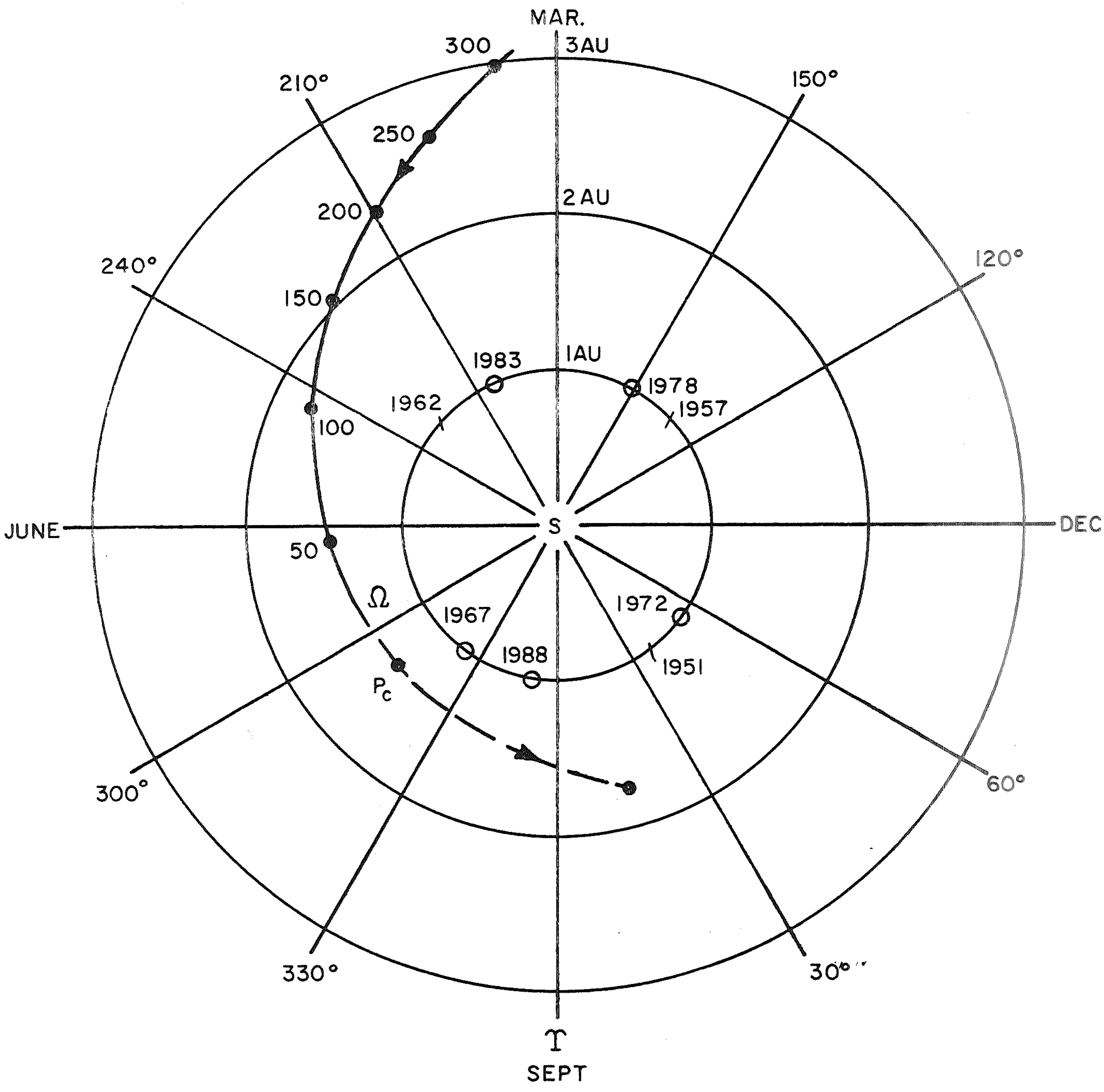


FIG A-9b. DISTANCE & ELONGATION FOR TEMPLE-2/88

TEMPLE 2



P_c = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELION OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET (SEE SECT. 2·3)

FIG. A-9c

TABLE A-9

OSCULATING ORBITAL ELEMENTS FOR COMET TEMPLE 2

Epoch: Calendar	Epoch: Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
5/16/62	2,437,800.5	3.024	0.549	12.48	119.28	191.03	8/14/67
2/8/65	2,438,800.5	3.023	0.548	12.48	119.28	191.00	8/13/67
4/19/67	2,439,600.5	3.025	0.548	12.48	119.27	190.95	8/13/67
11/5/67	2,439,800.5	3.026	0.548	12.47	119.27	190.95	11/16/72
8/1/70	2,440,800.5	3.023	0.548	12.48	119.27	190.88	11/14/72
10/9/72	2,441,600.5	3.024	0.549	12.48	119.27	190.85	11/13/72
4/27/73	2,441,800.5	3.024	0.549	12.48	119.27	190.85	2/16/78
7/6/75	2,442,600.5	3.026	0.548	12.48	119.27	190.93	2/18/78
9/13/77	2,443,400.5	3.028	0.548	12.47	119.25	190.91	2/19/78
4/1/78	2,443,600.5	3.028	0.548	12.47	119.25	190.90	5/28/83
12/26/80	2,444,600.5	3.032	0.546	12.45	119.25	190.97	5/30/83
3/6/83	2,445,400.5	3.036	0.545	12.44	119.16	190.89	5/30/83
9/22/83	2,445,600.5	3.035	0.545	12.44	119.16	190.90	9/12/88
5/14/85	2,446,200.5	3.037	0.545	12.44	119.15	190.95	9/13/88

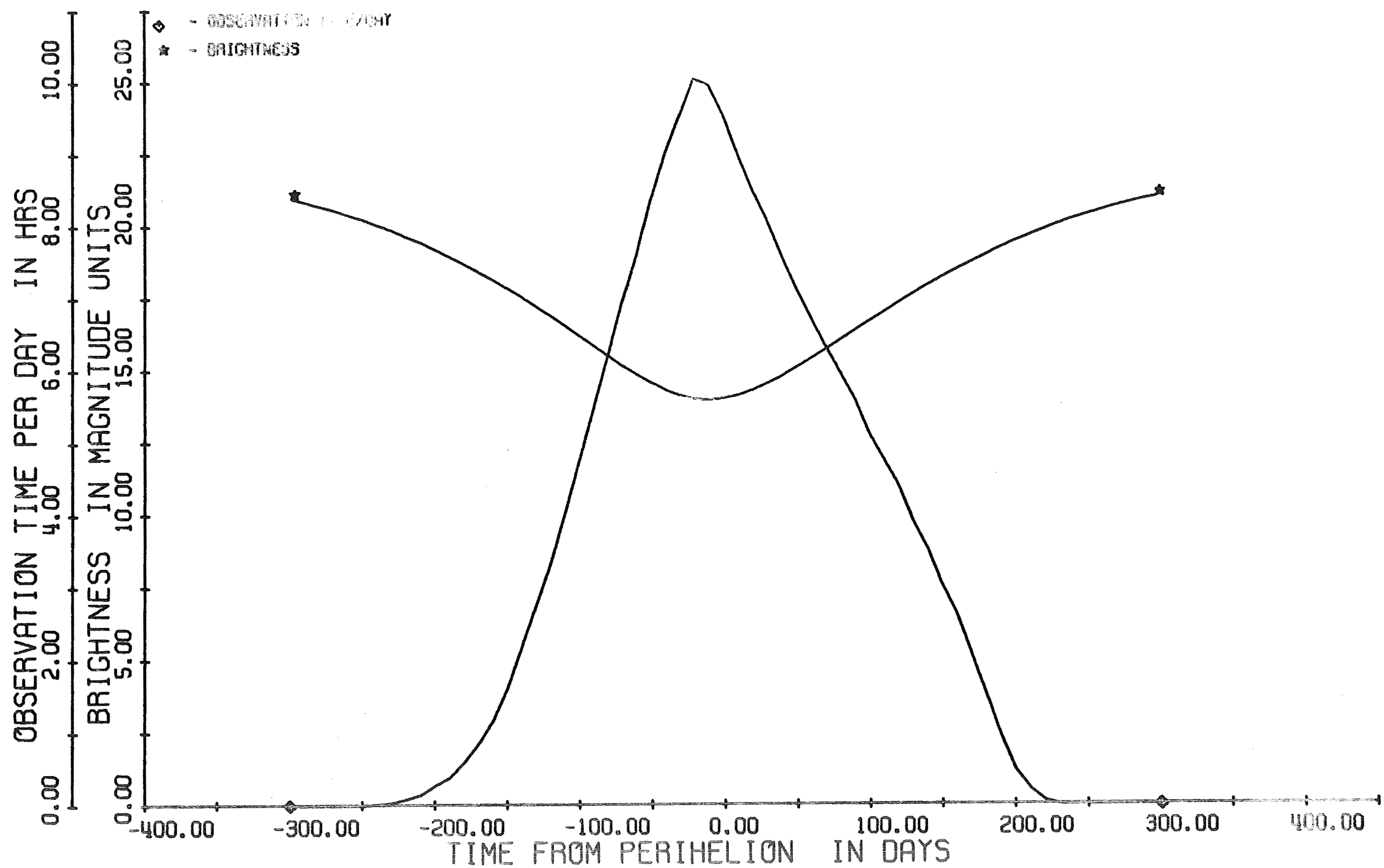


FIG A-10a. SIGHTING CONDITIONS FOR FAYE/91

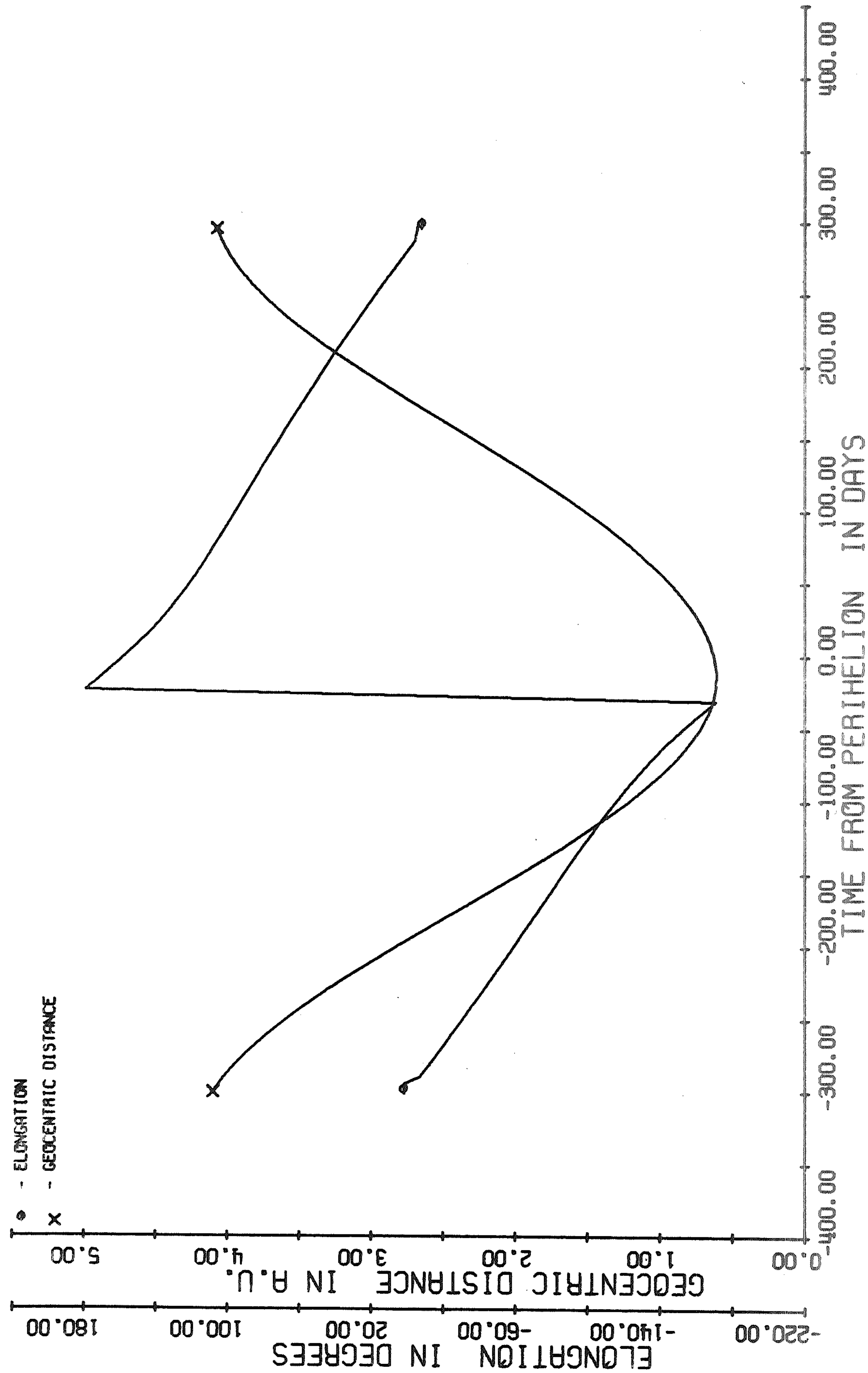
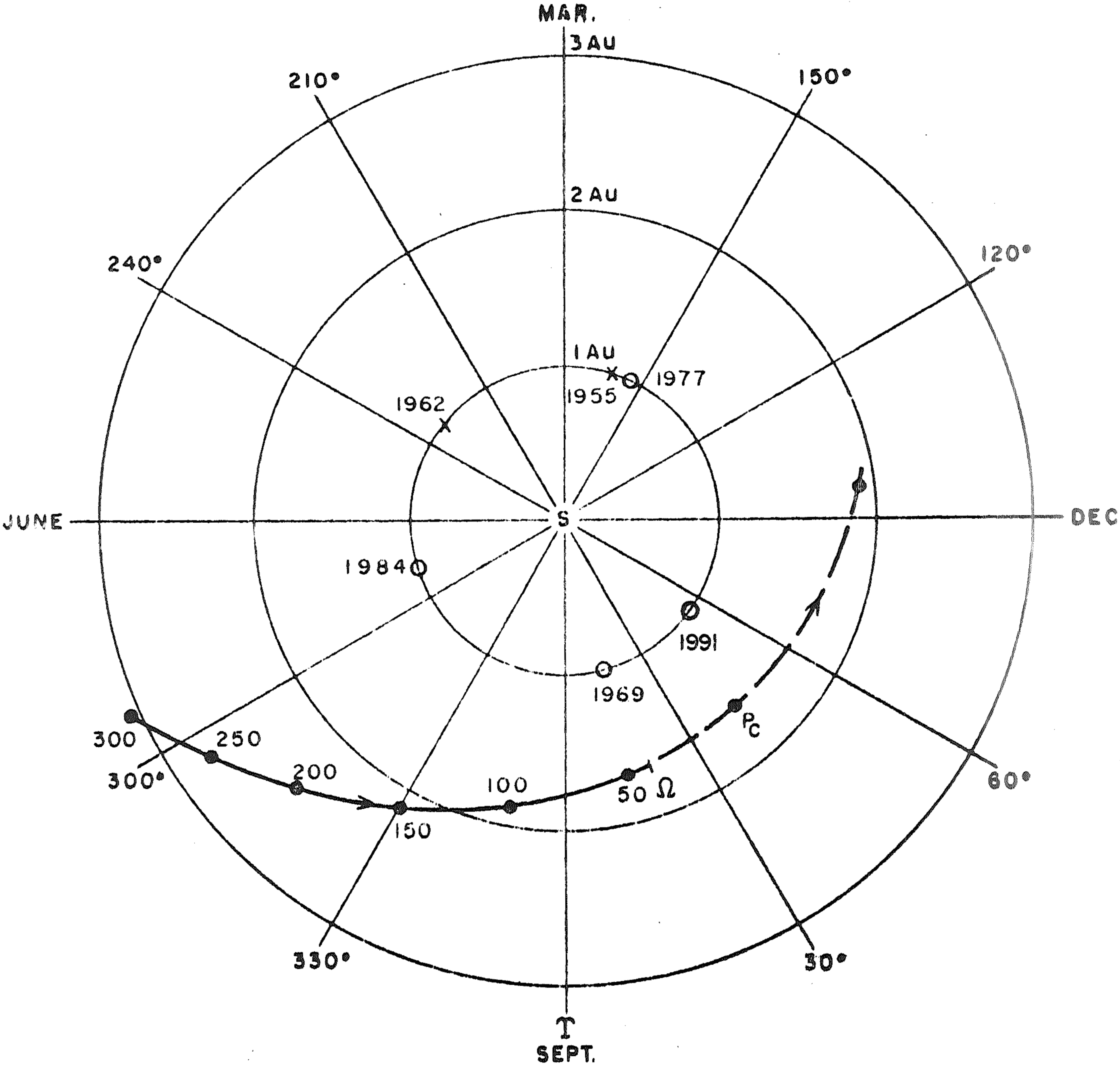


FIG A-10b. DISTANCE & ELONGATION FOR FAYE/91

FAYE



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-10c

TABLE A-10

OSCULATING ORBITAL ELEMENTS FOR COMET FAYE

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
5/16/62	2,437,800.5	3.790	0.576	9.10	199.12	203.56	9/29/69
3/15/66	2,439,200.5	3.797	0.576	9.09	199.10	203.71	10/6/69
6/27/69	2,440,400.5	3.800	0.575	9.08	199.04	203.68	10/7/69
1/13/70	2,440,600.5	3.800	0.575	9.08	199.04	203.68	3/4/77
11/13/73	2,442,000.5	3.796	0.575	9.09	199.06	203.61	2/28/77
2/25/77	2,443,200.5	3.793	0.576	9.09	199.08	203.67	2/27/77
9/13/77	2,443,400.5	3.792	0.576	9.09	199.07	203.66	7/17/84
12/26/80	2,444,600.5	3.788	0.576	9.10	199.06	203.55	7/12/84
4/9/84	2,445,800.5	3.7[illegible]	0.578	9.09	198.98	203.84	7/9/84
10/26/84	2,446,000.5	3.779	0.578	9.09	198.98	203.84	11/14/91

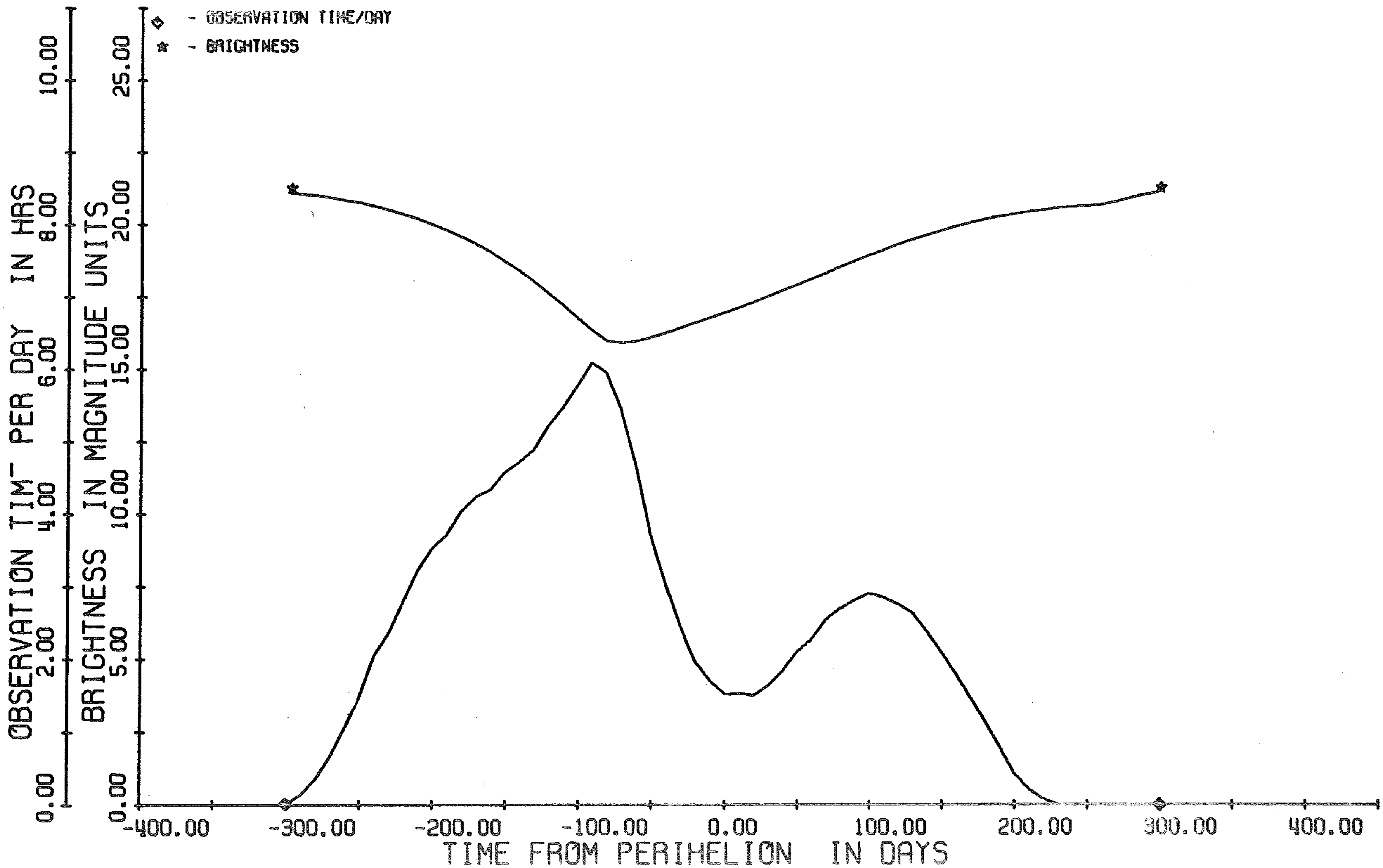


FIG A-11a. SIGHTING CONDITIONS FOR FORBES/93

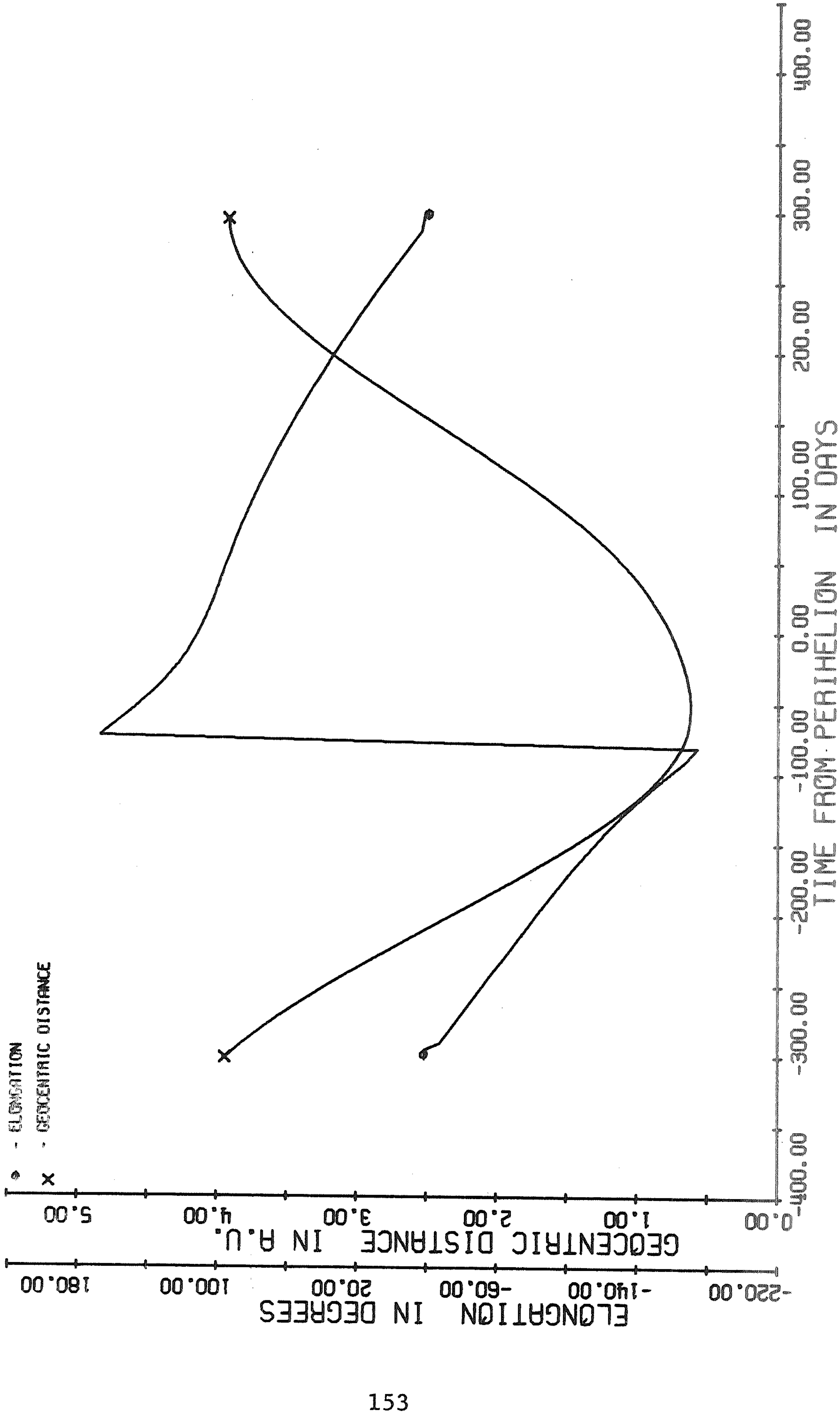
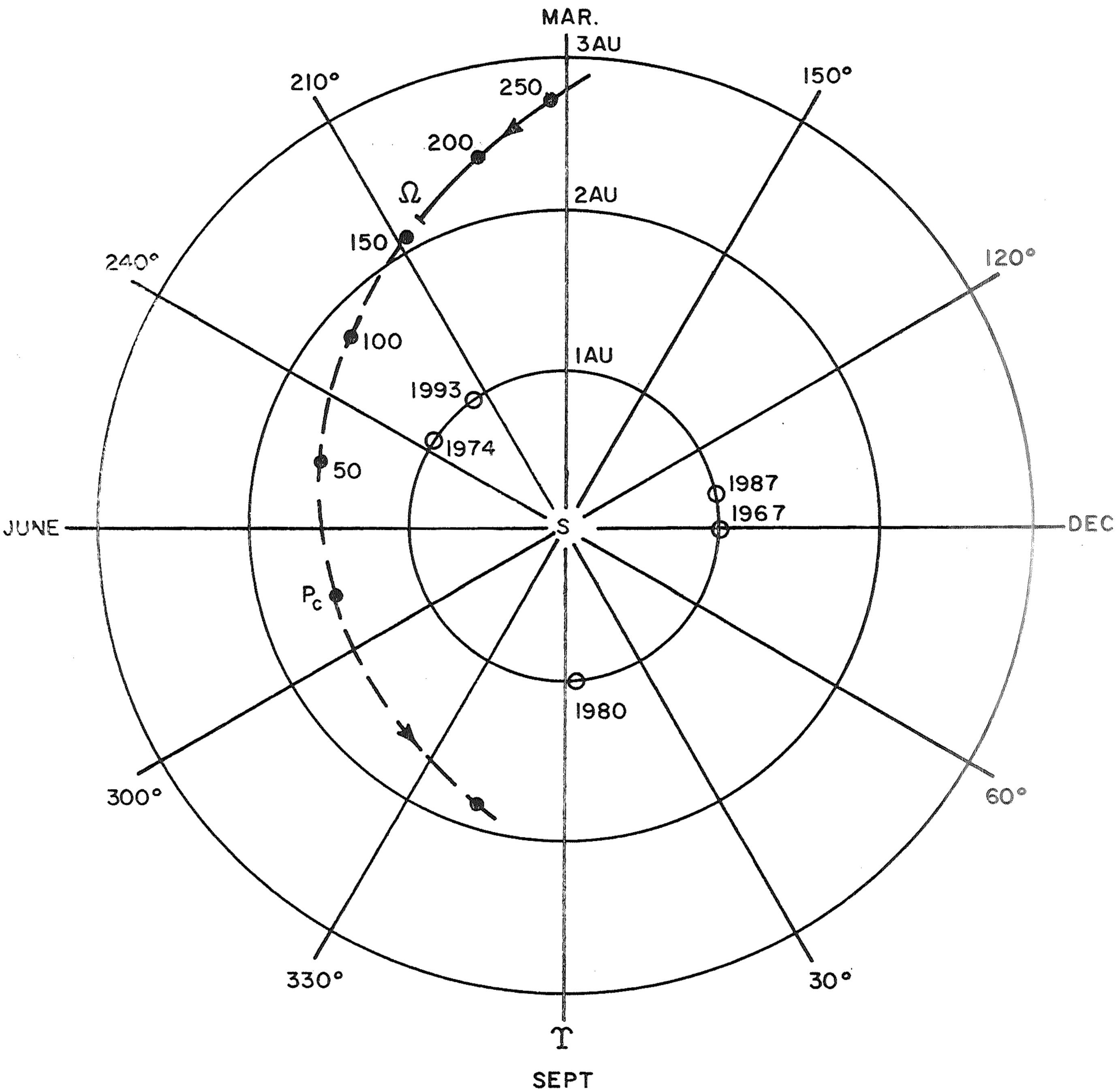


FIG A-IIb. DISTANCE & ELONGATION FOR FORBES/93

FORBES



P_c = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

⊘ = PAST POSITIONS OF EARTH AT PERIHELION OF COMET

○ = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET (SEE SECT. 2·3)

FIG. A-11c

Table A-11

OSCULATING ORBITAL ELEMENTS FOR COMET FORBES

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
2/11/55	2,435,150.5	3.461	0.551	4.62	25.45	259.69	2/17/55
8/30/55	2,435,350.5	3.461	0.551	4.62	25.44	259.69	7/27/61
5/26/58	2,436,350.5	3.457	0.552	4.62	25.44	259.61	7/24/61
2/19/61	2,437,350.5	3.454	0.553	4.62	25.40	259.73	7/24/61
9/7/61	2,437,550.5	3.456	0.553	4.62	25.39	259.73	12/26/67
12/20/64	2,438,750.5	3.454	0.552	4.62	25.38	259.66	12/22/67
9/16/67	2,439,750.5	3.451	0.553	4.62	25.29	259.81	12/21/67
4/3/68	2,439,950.5	3.452	0.554	4.62	25.29	259.81	5/21/74
7/17/71	2,441,150.5	3.449	0.555	4.62	25.26	259.78	5/19/74
4/12/74	2,442,150.5	3.445	0.555	4.62	25.20	259.93	5/19/74
10/29/74	2,442,350.5	3.446	0.555	4.62	25.20	259.92	10/11/80
2/10/78	2,443,550.5	3.432	0.559	4.62	24.73	260.05	9/27/80
3/17/79	2,443,950.5	3.412	0.565	4.65	23.30	261.95	9/23/80
4/20/80	2,444,350.5	3.400	0.565	4.66	23.06	262.50	9/24/80
11/6/80	2,444,550.5	3.400	0.565	4.66	23.06	262.51	1/1/87
1/15/83	2,445,350.5	3.400	0.565	4.66	23.04	262.51	1/1/87
10/11/85	2,446,350.5	3.398	0.566	4.66	22.95	262.66	1/1/87

~ 3/10/93

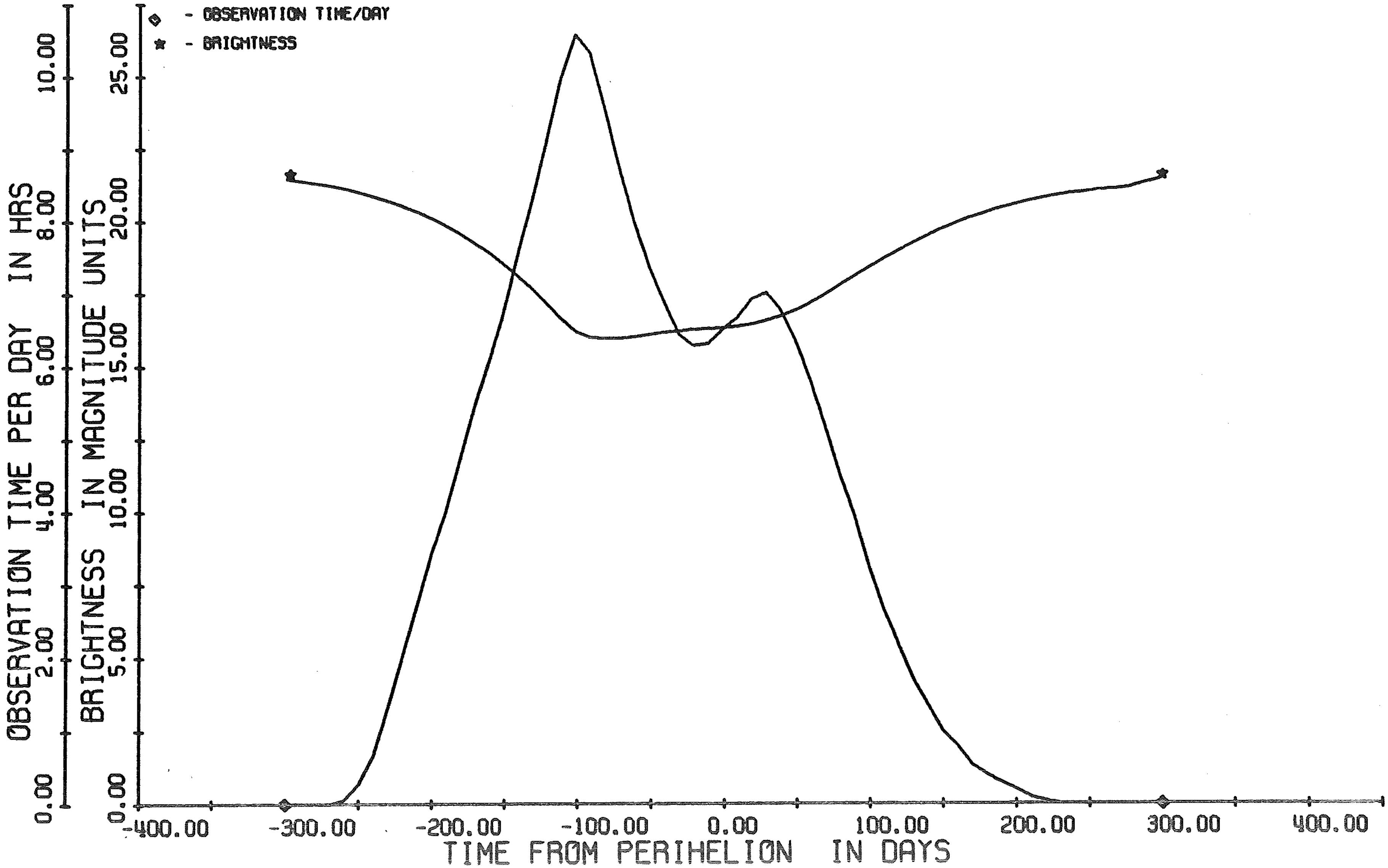


FIG A-12a. SIGHTING CONDITIONS FOR SCHAUMASSE/93

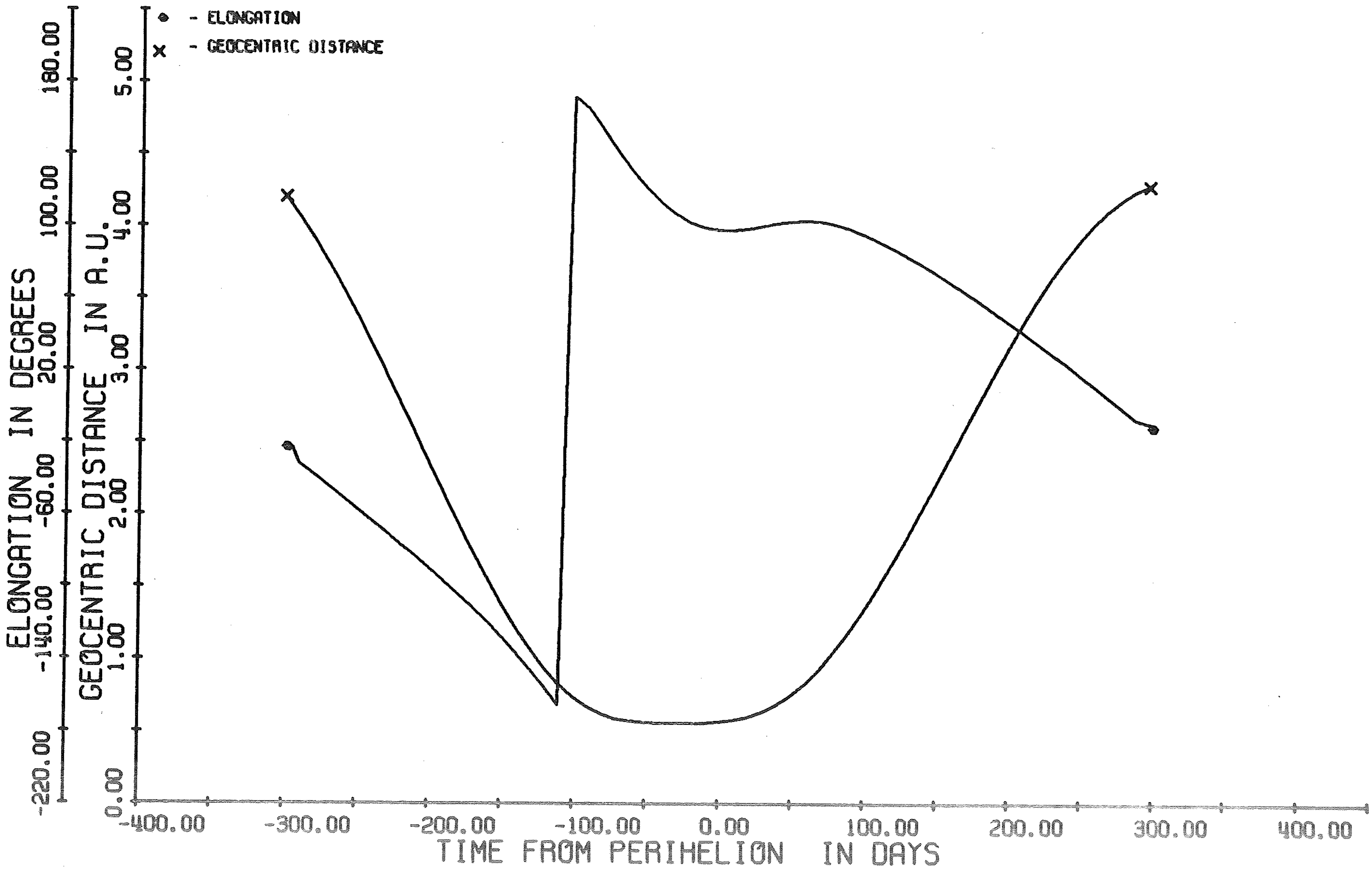
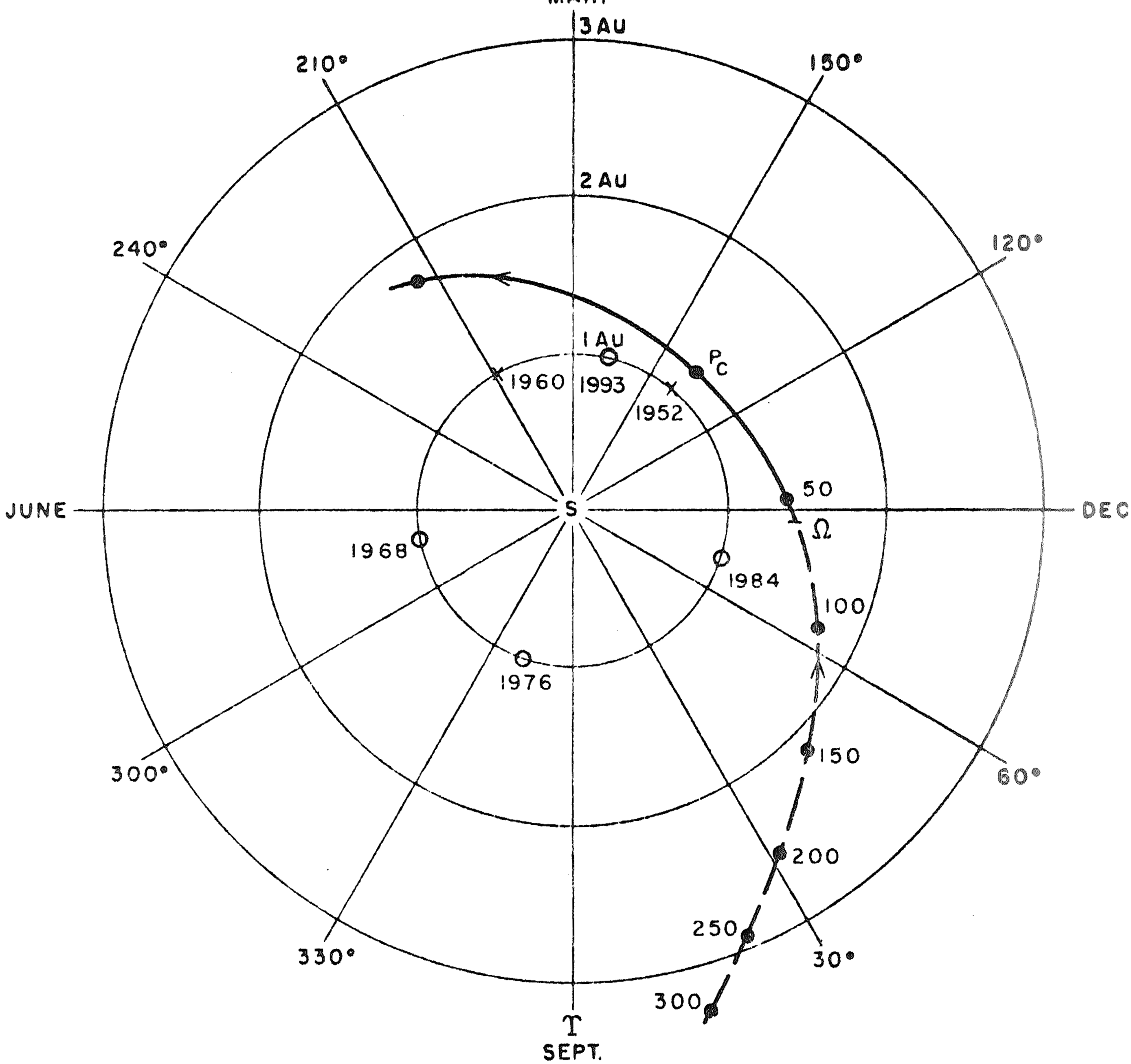


FIG A-12b. DISTANCE & ELONGATION FOR SCHAUMASSE/93

SCHAUMASSE



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-12c

TABLE A-12

OSCULATING ORBITAL ELEMENTS FOR COMET SCHAUMASSE

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
4/25/60	2,437,050.5	4.060	0.705	12.02	86.25	51.94	6/21/68
8/8/63	2,438,250.5	4.072	0.704	11.95	86.14	52.31	7/4/68
12/25/67	2,439,850.5	4.066	0.704	11.93	85.96	52.56	7/3/68
7/12/68	2,440,050.5	4.066	0.705	11.93	85.96	52.57	9/14/76
7/21/74	2,442,250.5	4.064	0.707	11.87	85.04	53.34	9/3/76
2/6/75	2,442,450.5	4.077	0.708	11.81	82.43	55.71	9/2/76
8/25/75	2,442,650.5	4.083	0.705	11.84	80.76	57.09	9/3/76
3/12/76	2,442,850.5	4.078	0.705	11.86	80.55	57.27	9/3/76
9/28/76	2,443,050.5	4.075	0.704	11.86	80.55	57.29	11/25/84
9/2/81	2,444,850.5	4.082	0.704	11.84	80.44	57.47	12/3/84
5/29/84	2,445,850.5	4.085	0.703	11.84	80.40	57.44	12/4/84
12/15/84	2,446,050.5	4.086	0.703	11.84	80.40	57.43	3/8/93
1/19/86	2,446,450.5	4.085	0.703	11.84	80.40	57.44	3/7/93

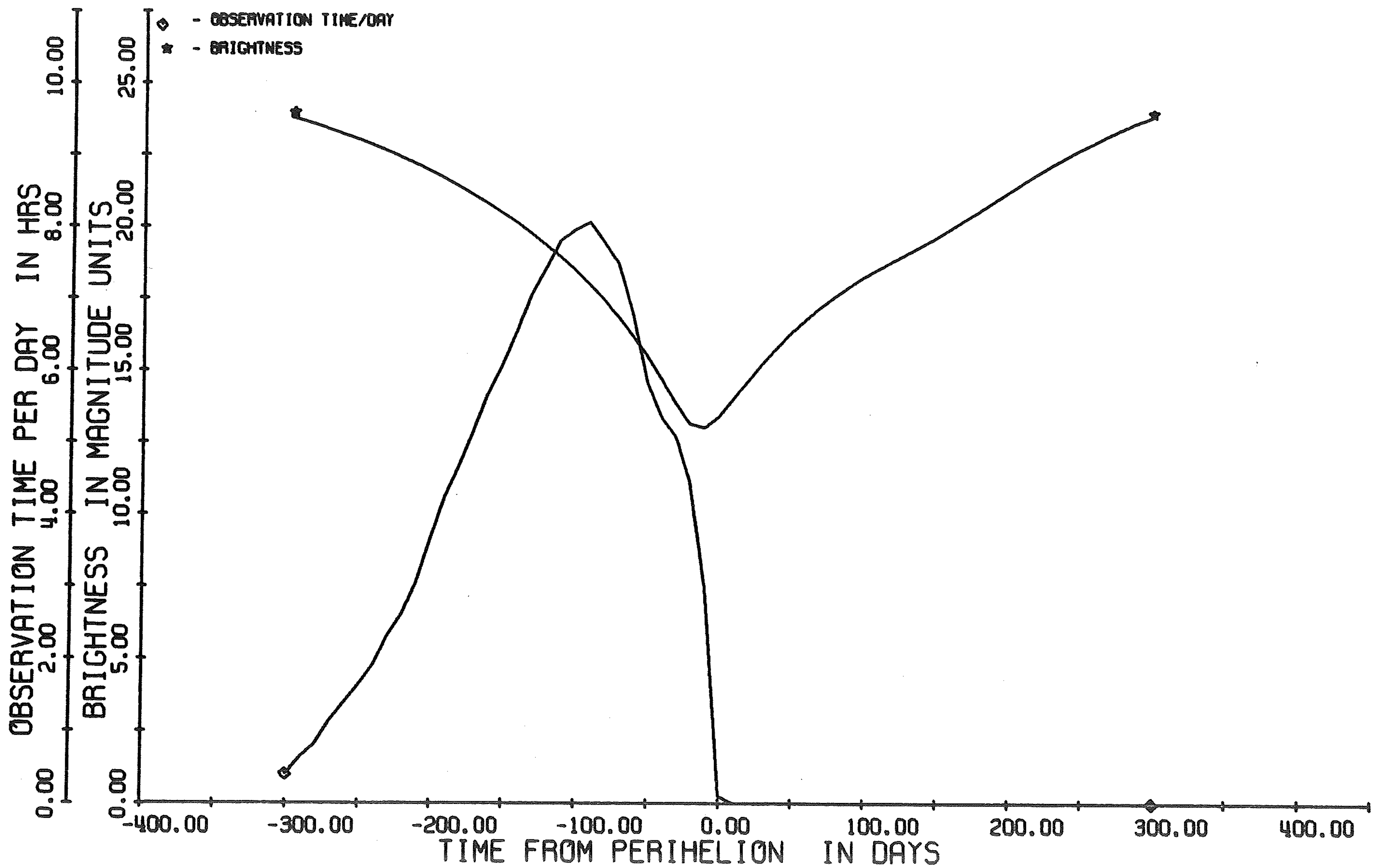


FIG A-13a. SIGHTING CONDITIONS FOR TUTTLE/94

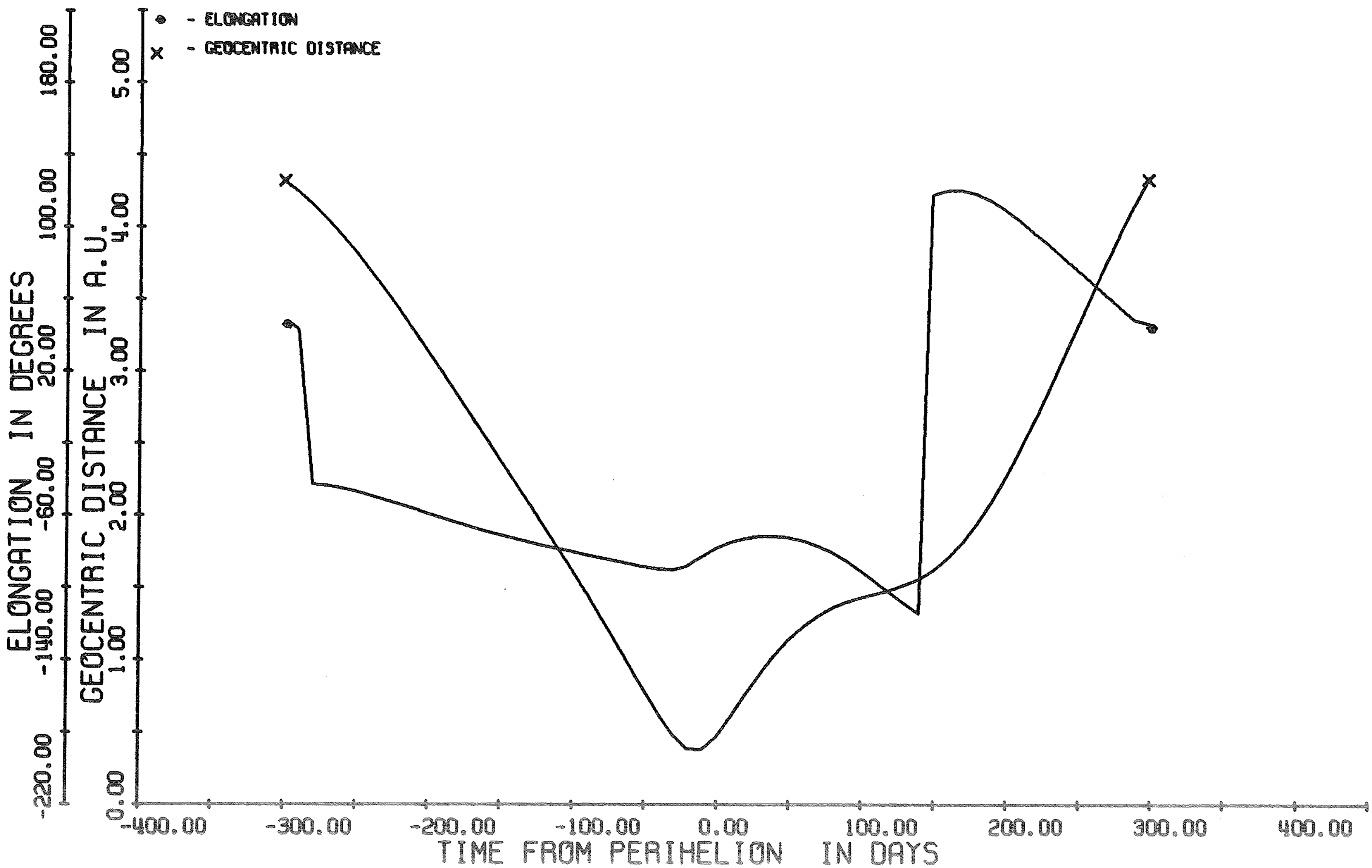
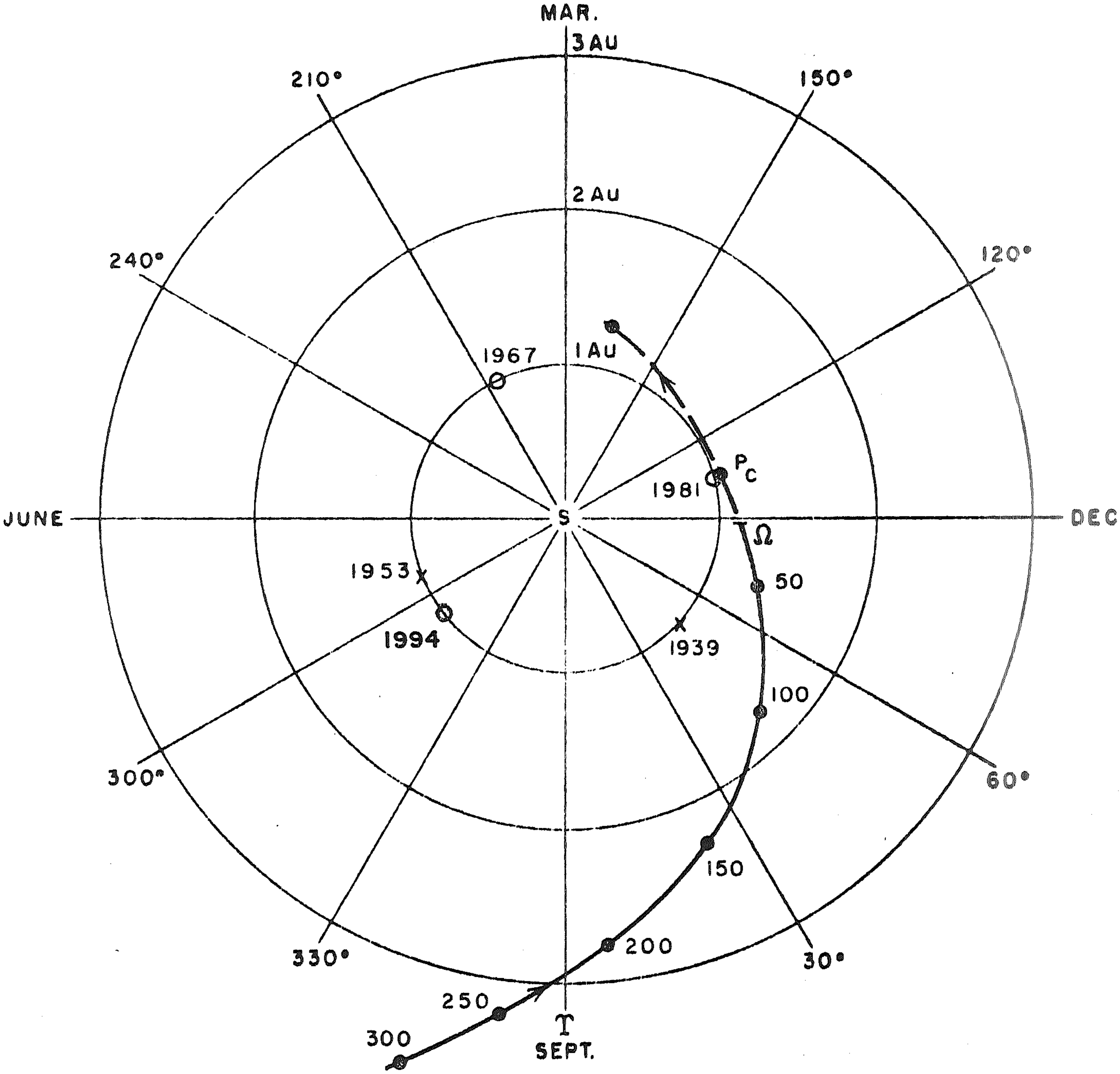


FIG A-13b. DISTANCE & ELONGATION FOR TUTTLE/94

TUTTLE



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-13c

TABLE A-13

OSCULATING ORBITAL ELEMENTS FOR COMET TUTTLE

Epoch: Calendar	Epoch: Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
3/14/53	2,434,450.5	5.741	0.821	54.47	269.75	206.94	7/12/53
9/29/53	2,434,650.5	5.741	0.821	54.47	269.75	206.93	4/15/67
4/25/60	2,437,050.5	5.749	0.821	54.31	269.71	206.97	4/23/67
11/20/66	2,439,450.5	5.747	0.822	54.38	269.80	206.92	4/16/67
6/8/67	2,439,650.5	5.748	0.822	54.38	269.79	206.92	1/25/81
7/21/74	2,442,250.5	5.739	0.821	54.36	269.83	206.81	1/7/81
7/29/80	2,444,450.5	5.725	0.823	54.47	269.89	206.90	1/5/81
2/14/81	2,444,650.5	5.723	0.823	54.47	269.89	206.90	9/15/94
11/11/83	2,445,650.5	5.700	0.822	54.58	269.87	206.78	8/14/94
12/15/84	2,446,050.5	5.689	0.822	54.58	269.87	206.70	7/30/94

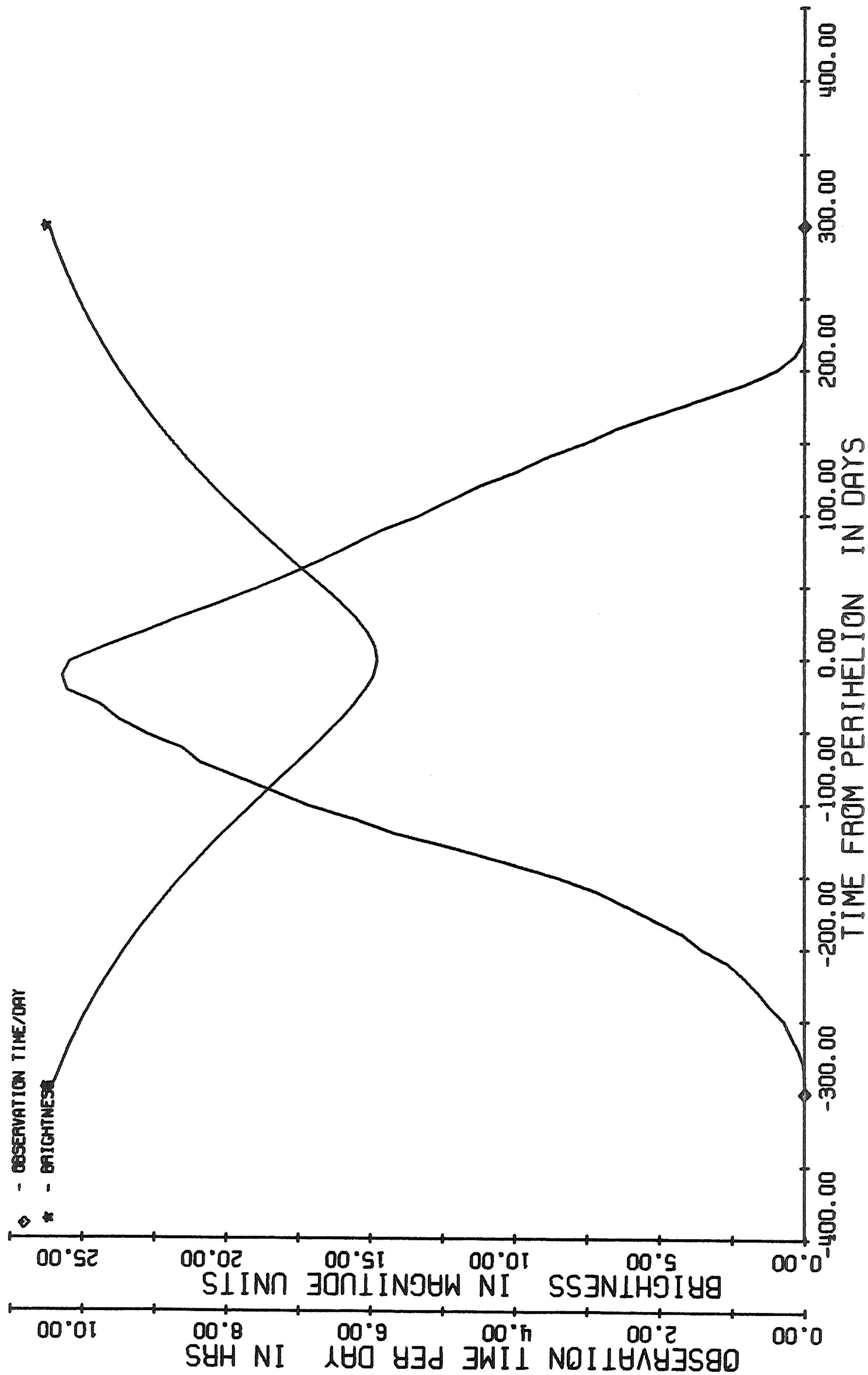


FIG A-14a. SIGHTING CONDITIONS FOR PERRINE-MRKOS/95

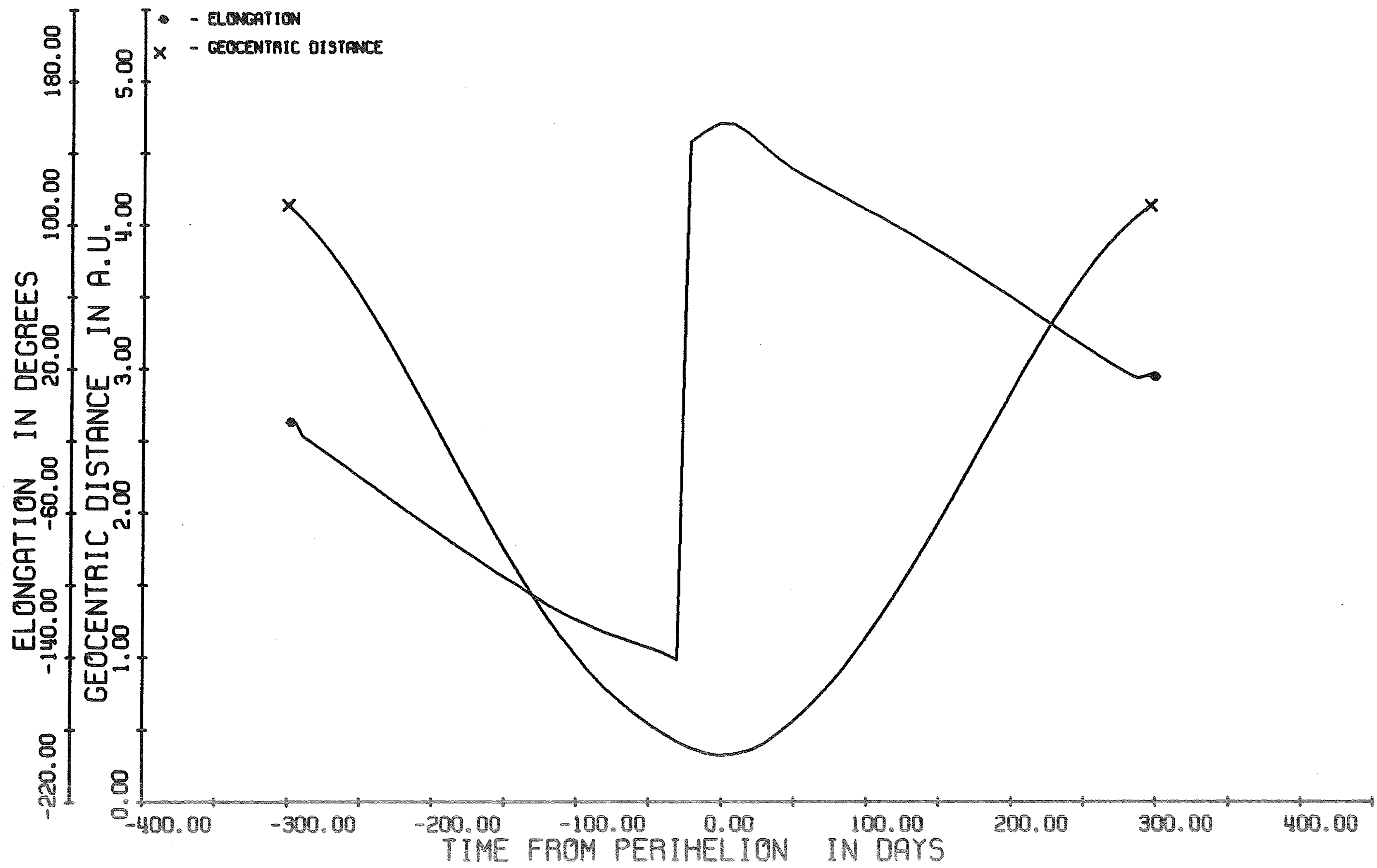
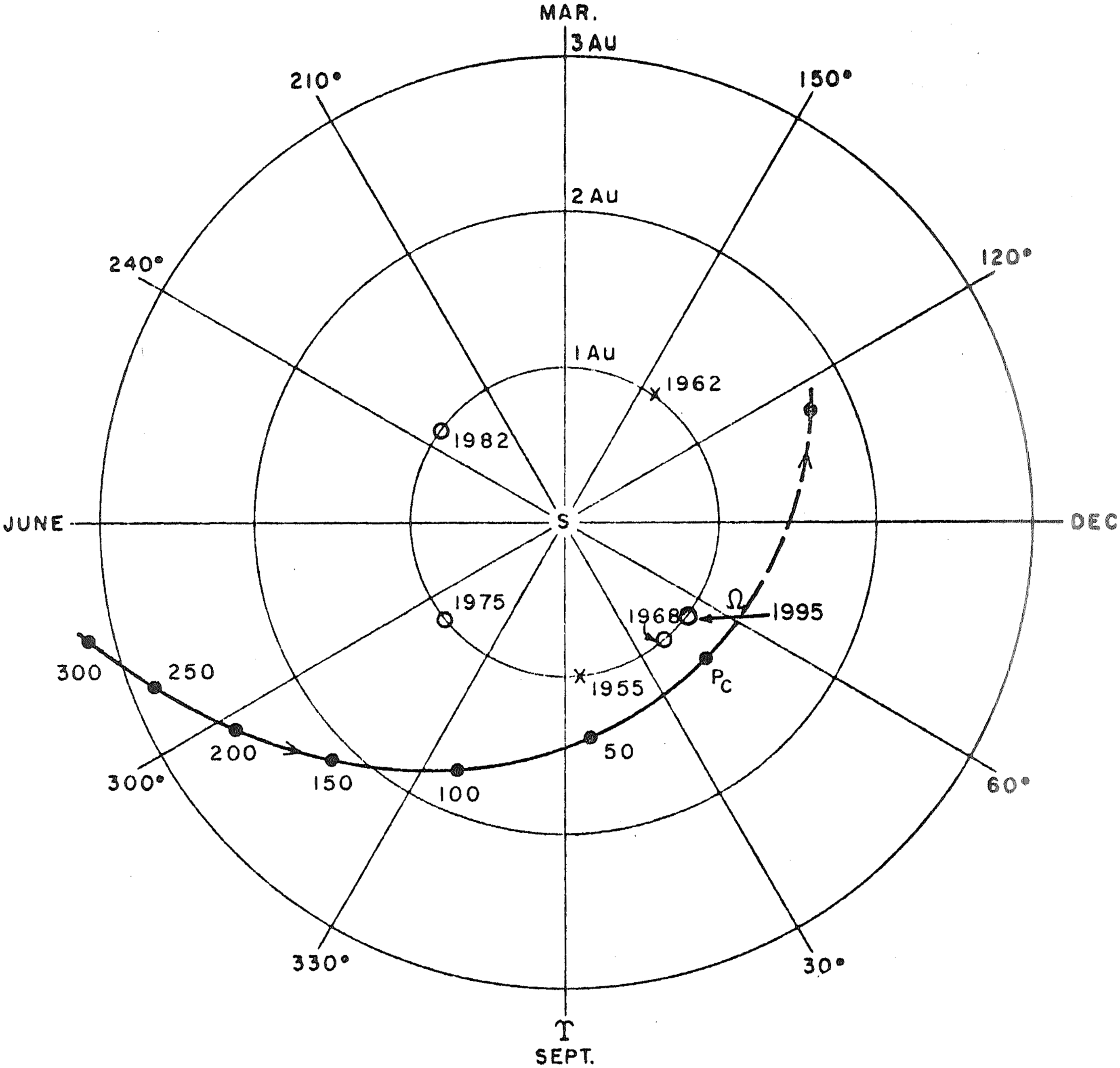


FIG A-14b. DISTANCE & ELONGATION FOR PERRINE-MRKOS/95

PERRINE-MRKOS



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-14c

TABLE A-14

OSCULATING ORBITAL ELEMENTS FOR COMET PERRINE-MRKOS

Epoch Calendar	Epoch Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
2/5/62	2,437,700.5	3.556	0.644	17.7[illegible]	240.27	165.95	2/11/62
8/23/62	2,437,900.5	3.557	0.644	17.74	240.27	165.96	10/27/68
12/5/65	2,439,100.5	3.559	0.644	17.75	240.23	166.06	10/30/68
8/31/68	2,440,100.5	3.561	0.643	17.74	240.21	166.05	10/31/68
3/19/69	2,440,300.5	3.560	0.643	17.74	240.21	166.07	7/20/75
7/1/72	2,441,500.5	3.577	0.638	17.80	239.96	166.59	8/2/75
3/28/75	2,442,500.5	3.582	0.639	17.79	239.95	166.50	8/2/75
10/14/75	2,442,700.5	3.581	0.639	17.79	239.95	166.50	5/12/82
1/26/79	2,443,900.5	3.586	0.638	17.78	239.95	166.58	5/16/82
5/10/82	2,445,100.5	3.590	0.637	17.76	239.95	166.51	5/16/82
11/26/82	2,445,300.5	3.589	0.637	17.76	239.95	116.50	3/4/89
8/22/85	2,446,300.5	3.587	0.637	17.77	239.92	166.48	3/1/89

~ 12/18/95

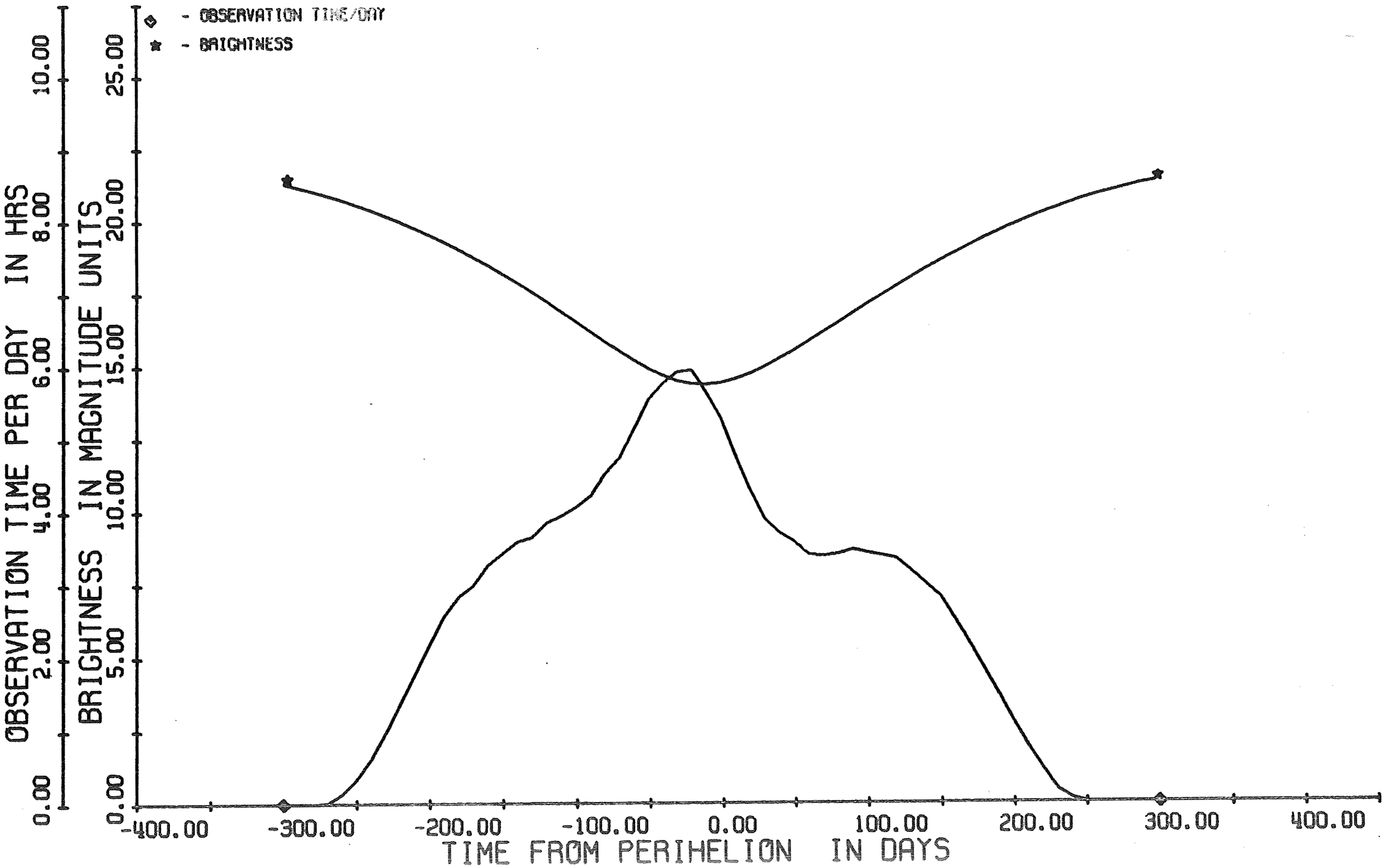


FIG A-15a. SIGHTING CONDITIONS FOR KOPFF/96

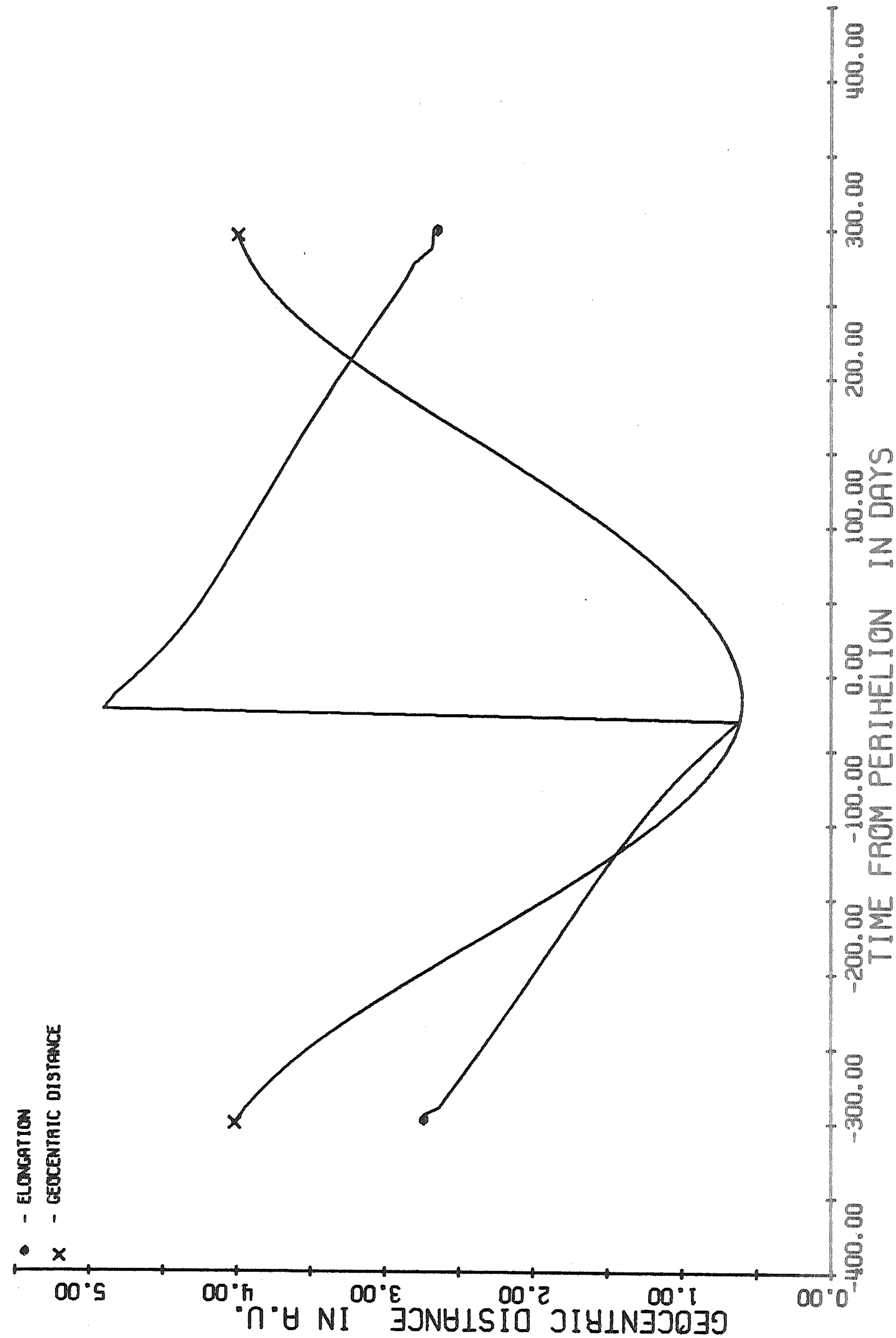
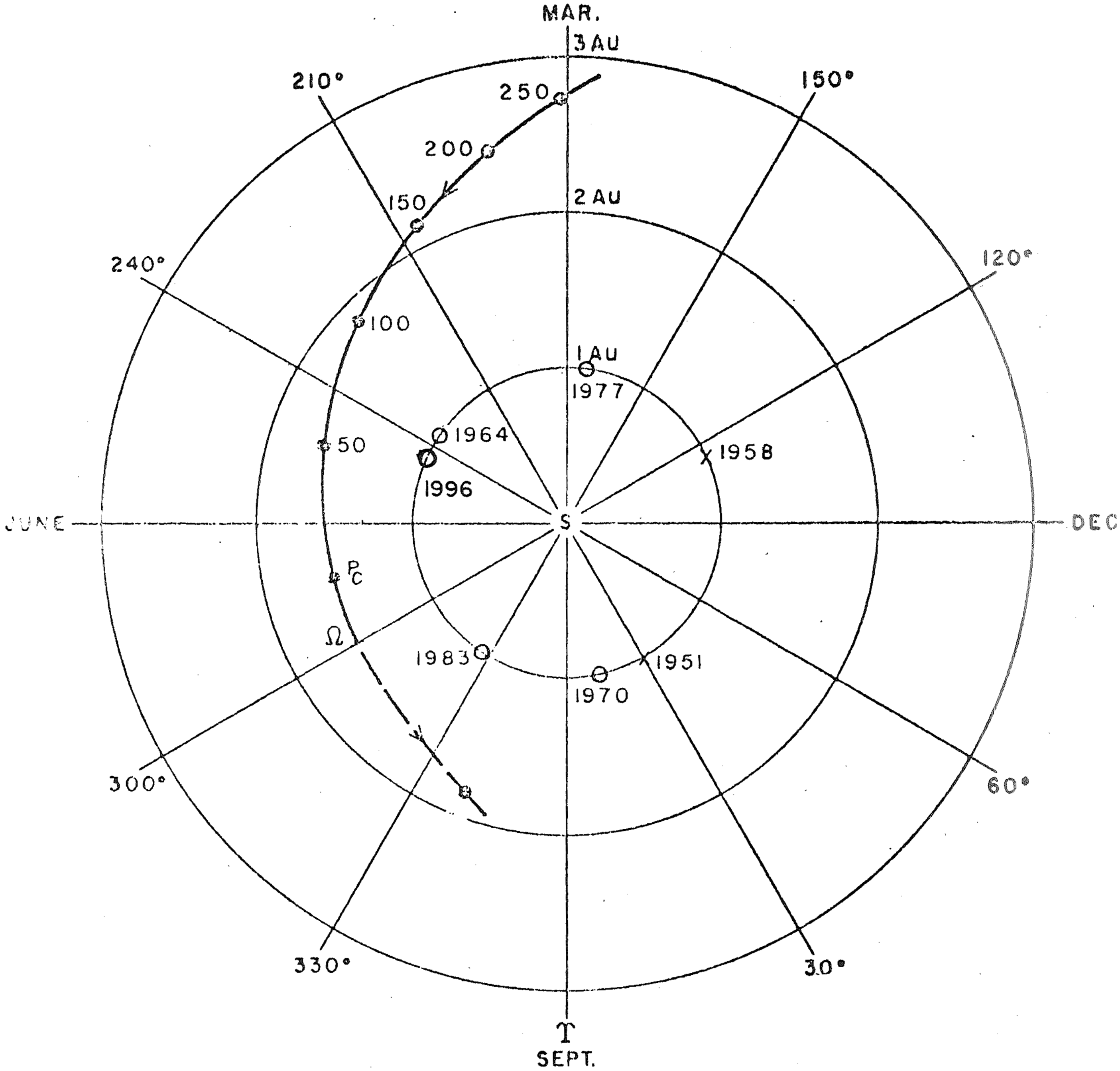


FIG A-15b. DISTANCE & ELONGATION FOR KOPFF/96

KOPFF



P_C = PERIHELION OF COMET

○ = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

◯ = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-15c

TABLE A-15

OSCULATING ORBITAL ELEMENTS FOR COMET KOPFF

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
4/15/64	2,438,500.5	3.418	0.555	4.71	120.91	161.91	5/18/64
10/31/64	2,438,700.5	3.419	0.555	4.71	120.91	161.93	9/11/70
12/5/65	2,439,100.5	3.430	0.555	4.72	120.70	162.48	9/24/70
6/23/66	2,439,300.5	3.438	0.552	4.73	120.54	162.87	10/1/70
4/23/70	2,440,700.5	3.456	0.547	4.73	120.45	162.72	10/6/70
11/9/70	2,440,900.5	3.454	0.547	4.73	120.44	162.73	3/8/77
2/21/74	2,442,100.5	3.459	0.547	4.73	120.40	162.89	3/13/77
11/17/76	2,443,100.5	3.460	0.546	4.73	120.39	162.87	3/14/77
6/5/77	2,443,300.5	3.460	0.546	4.73	120.39	162.87	8/20/83
9/17/80	2,444,500.5	3.460	0.545	4.73	120.38	162.86	8/19/83
6/14/83	2,445,500.5	3.463	0.545	4.73	120.37	162.78	8/18/83
12/31/83	2,445,700.5	3.462	0.545	4.73	120.36	162.77	1/26/90
8/22/85	2,446,300.5	3.465	0.545	4.73	120.36	162.85	1/29/90

7/20/96

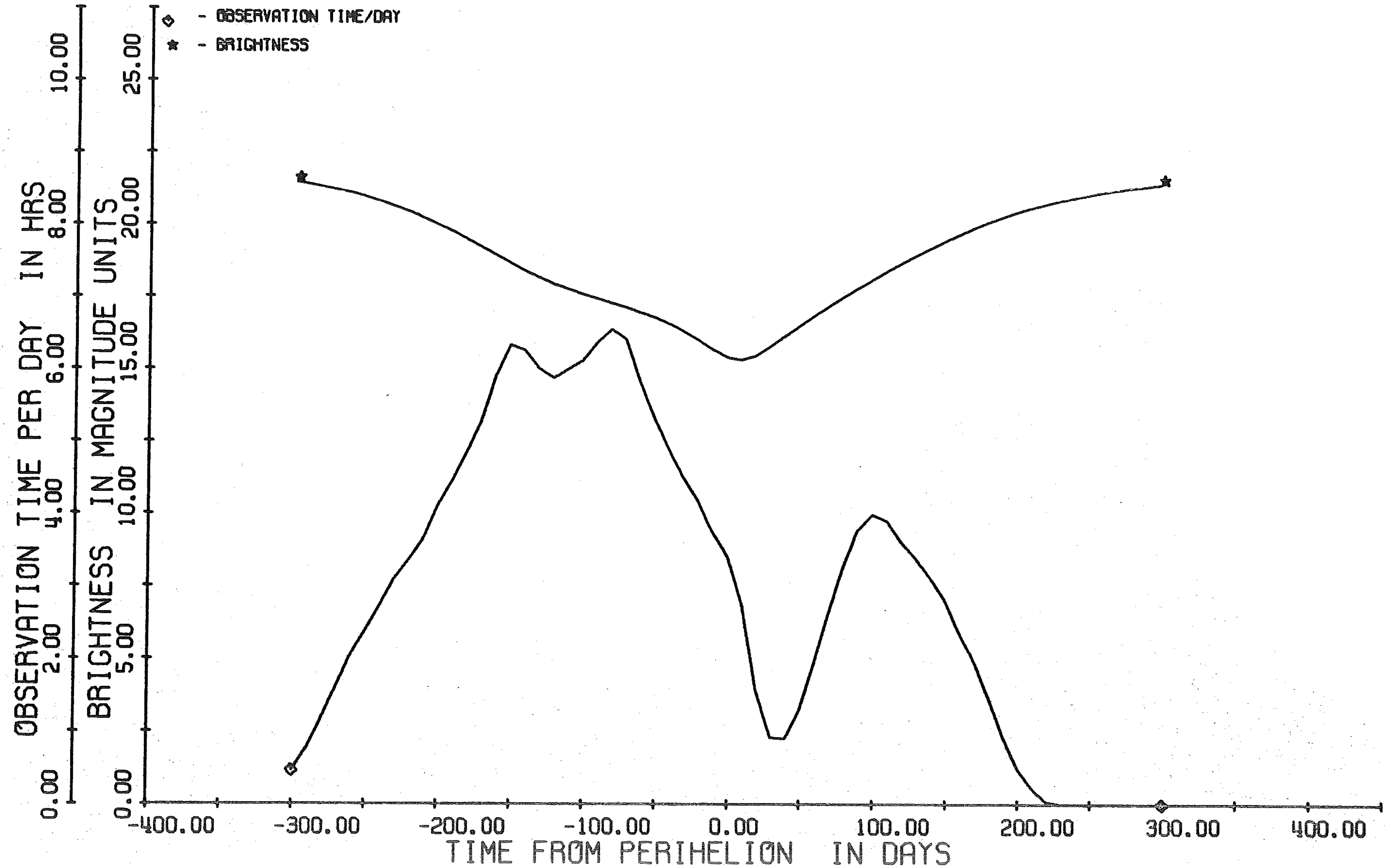


FIG A-16a. SIGHTING CONDITIONS FOR GIACOBINI-ZINNER/98

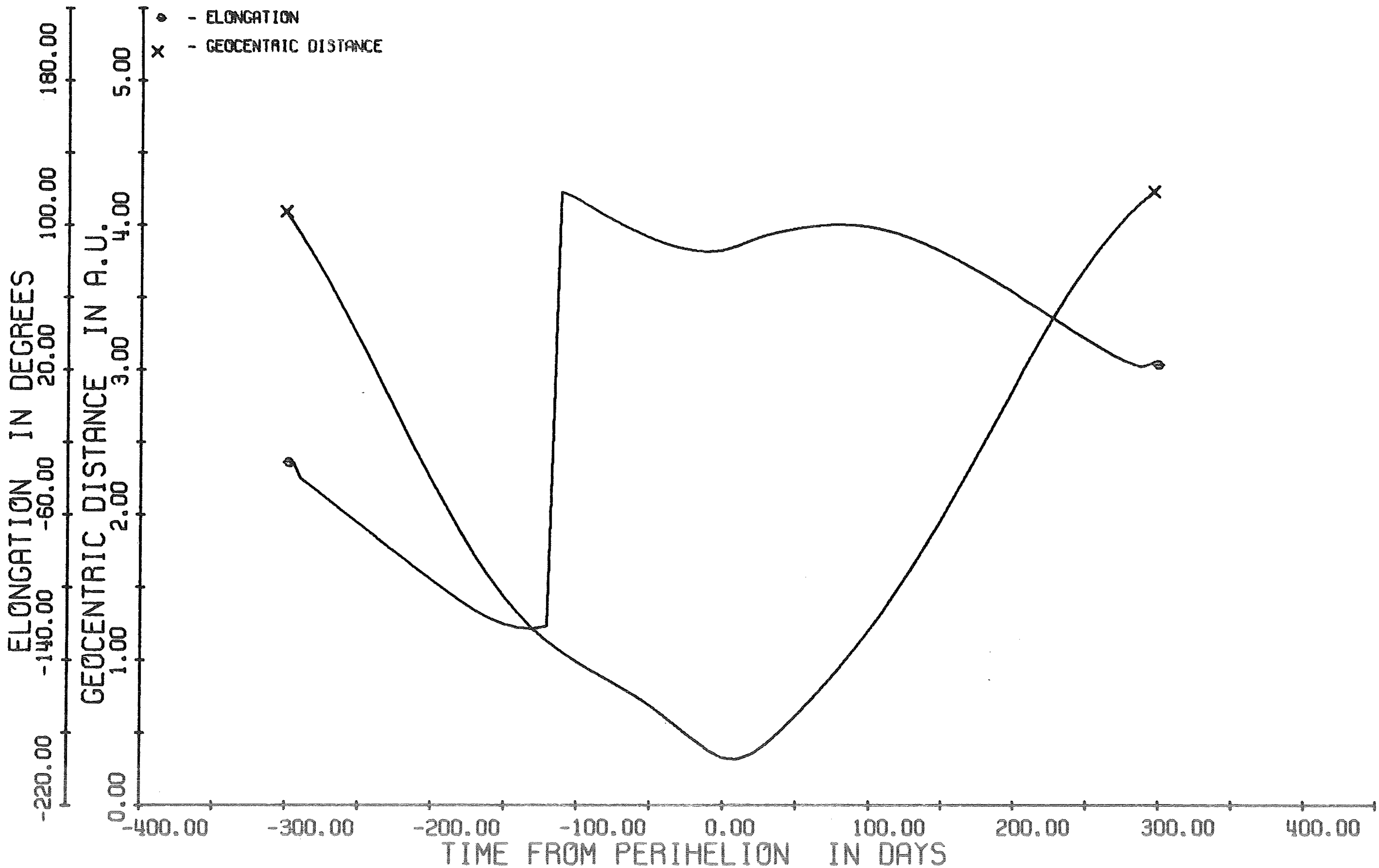
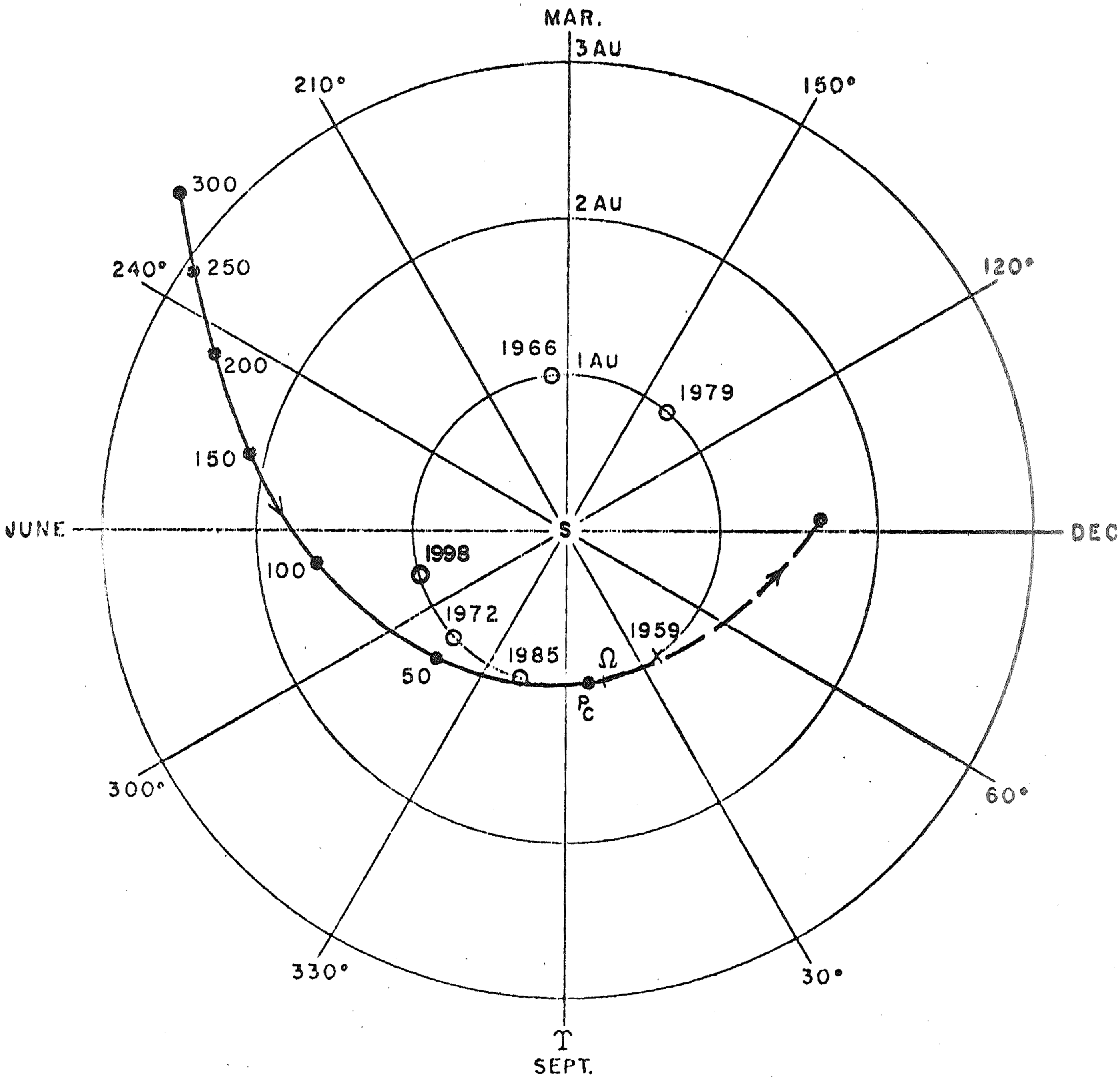


FIG A-16b. DISTANCE & ELONGATION FOR GIACOBINI-ZINNER/98

GIACOBINI-ZINNER



P_C = PERIHELION OF COMET

● = POSITION OF COMET AT STATED NUMBER OF DAYS BEFORE PERIHELION

X = PAST POSITIONS OF EARTH AT PERIHELON OF COMET

O = PREDICTED POSITIONS OF EARTH AT PERIHELION OF COMET

FIG. A-16c

TABLE A-16

OSCULATING ORBITAL ELEMENTS FOR COMET GIACOBINI-ZINNER

Epoch							
Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
10/8/59	2,436,850.5	3.453	0.729	30.91	196.03	172.84	10/26/59
4/25/60	2,437,050.5	3.453	0.729	30.91	196.03	172.84	3/27/66
1/20/63	2,438,050.5	3.452	0.730	30.95	195.98	172.87	3/27/66
10/16/65	2,439,050.5	3.450	0.729	30.95	195.97	172.92	3/27/66
5/4/66	2,439,250.5	3.449	0.729	30.95	195.96	172.92	8/22/72
8/16/69	2,440,450.5	3.441	0.731	32.31	195.39	172.83	8/3/72
10/31/69	2,440,526.5	3.454	0.727	32.54	195.37	172.47	7/31/72
5/12/72	2,441,450.5	3.489	0.715	31.71	195.13	171.88	8/3/72
11/28/72	2,441,650.5	3.489	0.715	31.71	195.13	171.89	2/9/79
3/12/76	2,442,850.5	3.491	0.715	31.74	195.09	171.95	2/11/79
12/7/78	2,443,850.5	3.491	0.714	31.70	195.07	171.95	2/11/79
6/25/79	2,444,050.5	3.491	0.714	31.70	195.06	171.96	8/21/85
7/29/80	2,444,450.5	3.497	0.714	31.78	194.91	172.20	8/27/85
2/14/81	2,444,650.5	3.503	0.712	31.921	194.75	172.47	9/1/85
9/2/81	2,444,850.5	3.507	0.710	31.980	194.71	172.58	9/4/85
7/3/85	2,446,250.5	3.517	0.707	31.888	194.70	172.47	9/4/85

~ 4/11/92
~ 12/2/98